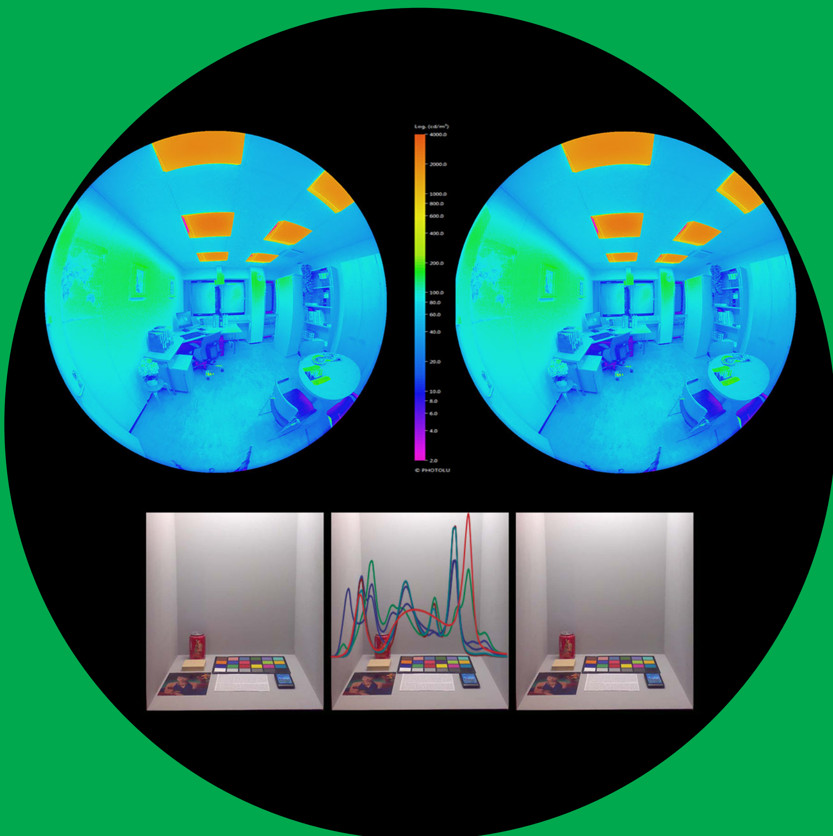
Department of Electrical Engineering and Automation

Subjective preference of light colour and LED lighting

Rajendra Dangol



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Subjective preference of light colour and LED lighting

Rajenda Dangol

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Abstract

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Abstract

The main objective of this work is to investigate the subjective preferences for lighting environments under different LED spectral power distributions (SPDs) and to analyse the different existing colour quality descriptors in order to recommend the best descriptor. An additional aim of the work is to find out the correlated colour temperature (CCT) and illuminance levels that users prefer for LED lighting. The experiments were conducted in lighting booths and in office rooms, where the subjective preferences for different LED light spectra were studied.

In the lighting booth experiments, seven different LED SPDs were studied at CCTs of 2700 K, 4000 K and 6500 K at 500 lux. The study showed that the observers preferred the LED SPDs which increased the object chroma and colourfulness values (calculated in CIECAM02-UCS). Also, the preferred LED SPDs had higher values of reference-based metrics (such as colour quality scale (CQS) colour preference scale) and higher values of area-based metrics (such as CQS colour gamut scale or gamut area index (GAI)). The observers preferred the light sources at CCT of 4000 K and 6500 K over the CCT of 2700 K.

The work was continued by simulation work and user acceptance studies to find out the simplified LED SPDs that the observers would prefer. The simulation results suggested that it is possible to generate simplified LED SPDs that have CQS Qp and CQS Qg values similar to those of the preferred complex SPDs that were generated by 9 to 11 different types of LEDs. The user acceptance studies conducted in the lighting booths also showed that the simplified LED SPDs using three different types of LEDs were preferred over complex LED SPD. Later, similar simplified LED SPDs were also studied in office rooms, and it was found that the observers preferred simplified LED SPDs over fluorescent lamp.

The three different LED SPDs at each CCT of 4000 K and 6500 K were studied in the office room experiments. The observers preferred most the LED SPDs with high CQS Qp and CQS Qg or GAI values and least the LED SPDs that had the lowest CQS Qp and CQS Qg values. Also, the light sources (having high CQS Qp and CQS Qg) with negative Duv values were more preferred over light sources with positive Duv values maintaining the Duv values within the limit of ±0.0054. Moreover, for the office lighting, the observers preferred CCT of 4000 K over CCT of 6500 K at 500 lux. It was also found that the observers preferred the illuminance level of 500 lux over 300 lux.

The results of the experiments conducted in the lighting booths to test the performance of different fidelity metrics showed that the CIE CRI, CRI2012 and CQS provide similar predictions for LED light sources that do not enhance the object chroma. It was found that the best prediction of colour fidelity was provided by CQS for LED light sources that enhance object chroma.

Keywords light emitting diode, preference, naturalness, colourfulness, colour rendering, colour quality, colour fidelity, office lighting

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Preface

The work presented in this thesis was performed at the Lighting Unit, Aalto University School of Electrical Engineering. Part of the work was carried out in the project "SSL4EU" funded by the European Commission in the Seventh Framework Programme. Another part of the work was carried out in the project "Light Energy" funded by Aalto University in the Aalto Energy Efficiency Research Programme. I am grateful for all these projects for their support.

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Espoo, April 2015
Rajendra Dangol

Contents

List of Abbreviations and Symbols

Abbreviations

ANOVA	Analysis Of Variance
CCT	Correlated Colour Temperature
CFL	Compact Fluorescent Lamp
CIE	Commission Internationale de l'Eclairage
CQS	Colour Quality Scale
CRI	Colour Rendering Index
ECG	Electronic Control Gear
FCI	Feeling of Contrast Index
FL	Fluorescent Lamp
GAI	Gamut Area Index
LED	Light Emitting Diode
LER	Luminous Efficacy of Radiation
MCC	Macbeth Colour Checker
MCRI	Memory Colour Rendering Index
MANOVA	Multivariate Analysis Of Variance
NIST	US National Institute of Standards and Technology
PSU	Power Supply Unit
RCRI	Rank Order Based Colour Rendering Index
SPD	Spectral Power Distribution
SPSS	Statistical Package for the Social Sciences

Symbols

Duv	Chromaticity difference measured in the CIE 1976 u'v' chromaticity diagram
p-value	The probability of statistical significance test
Qa	General Colour Quality Scale
Qg	Gamut Area Scale, a CQS supplementary metric
Qp	Colour Preference Scale, a CQS supplementary metric
Ra	CIE general colour rendering index

List of Publications

This doctoral dissertation consists of a summary and of the following publications that are referred to in the text by their numerals

I. Dangol, R; Islam, M; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. 2013. Subjective preferences and colour quality metrics of LED light sources. *Lighting Research and Technology*, volume 45, number 6, pages 666-688.

II. Islam, M; Dangol, R; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. 2013. User preferences for LED lighting in terms of light spectrum. *Lighting Research and Technology*, volume 45, number 6, pages 641-665.

III. Baniya, R.R; Dangol, R; Bhusal, P; Wilm, A; Baur, E ; Puolakka, M; Halonen, L. 2015. User-acceptance studies for simplified light-emitting diode spectra. *Lighting Research and Technology*, volume 47, number 2, pages 177-191.

IV. Dangol, R; Islam, M; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. 2015. User acceptance studies for LED office lighting: Preference, naturalness and colourfulness. *Lighting Research and Technology*, volume 47, number 1, pages 36-53.

V. Islam, M; Dangol, R; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. 2015. User acceptance studies for LED office lighting: lamp spectrum, spatial brightness and illuminance level. *Lighting Research and Technology*, volume 47, number 1, pages 54-79.

VI. Dangol, R; Bhusal, P; Halonen L. 2014. Performance of colour fidelity metrics. *Lighting Research and Technology*, first published online on October 22, 2014 as DOI: 10.1177/1477153514555721.

The author played a major role in all respects of the work presented in this thesis. He was the main author, and he analysed the results presented in Publications I, IV and VI. For Publication II, the author participated in the experimental measurements, calculations, data collection and was responsible for the simulation work. In Publication III, he was responsible for the part concerning optimizing the preferred LED spectra by simulation. He contributed to simulation work, measurements, experimental design and data collection for Publication V.

1. Introduction

1.1 Background

Light is electromagnetic radiation visible to human eyes and covers wavelengths in the approximate range between 380 to 780 nm. These wavelengths are associated with the human perception of different colours. Hence, colours have close link to the spectral characteristics of light. Commission International de l'Eclairage (CIE) has defined light as radiation that is considered from the point of view of its ability to excite the human visual system [1].

Colour is the characteristic of visual perception and can be perceived when there exist light, an object and an observer. When an object is illuminated by light, it absorbs certain wavelengths and reflects others based on the reflectance characteristics of the object surface. For example, if a green surface is illuminated by daylight, it absorbs most wavelengths but reflects mainly green, hence we see the object as green. Whereas, if a green object is illuminated by a low-pressure sodium lamp, the object looks black or grey. This is because the low-pressure sodium lamp produces radiation in the wavelengths related to yellow light. Therefore, the colour of the object depends on the spectral power distribution (SPD) of light source and the spectral reflectance characteristics of the object surface. In the past, when artificial illumination was not much developed, the SPD curve and colour temperature were used to describe how light from the lamp will affect the colour of objects. However, after the development of artificial light sources with different SPDs but having equal correlated colour temperature (CCT), the problem of colour rendering became serious [2]. In 1948, the CIE recommended an eight-band method to calculate the colour rendering of light sources [3], [4]. Later, it was found that the spectral band method did not work well with "de Luxe" type fluorescent lamps. However, the method based on colour shift gave good agreement with visual appraisal [3]. Therefore, in 1965, the CIE published the first edition of the method of measuring and specifying colour rendering properties of light sources, based on a test colour sample method such as CIE 13-1965 [3]. The method rates light sources in terms of the CIE colour rendering index (CRI). In 1974, the CIE published an updated version of this method. In this update, the major change was the introduction of the resultant colour shift. The resultant colour shift is the combination of an illuminant perceived colour shift and an adaptive perceived colour shift. The third edition CIE 13, in which some misprints found in the second edition were corrected, was published in 1995 [3]. However, no major changes in the method were introduced.

After the invention of tri-band fluorescent lamps, which were designed to have high luminous efficacy and high CIE CRI, the rating provided by the CIE CRI was questioned. The CIE CRI values of tri-band fluorescent lamps were high, but the visual colour rendering was poor. The CIE CRI has a number of shortcomings and problems (see subsection 2.1 for details). Again, after the emergence of the white light from light emitting diodes (LEDs), the problems of CIE CRI became serious enough. The ranking provided by the CIE CRI for white LEDs often contradicts the visual rankings [5]. However, the CIE CRI is still in use and CIE technical committees' are working to find out new solution(s).

LEDs have higher freedom in spectral design compared to the conventional light sources. LED lighting has huge potential to save energy and provides enormous opportunities to adjust the lighting according to actual needs in the working place. However, end-users' requirements, expectations and preferences for lighting applications based on LEDs are not well known. Therefore, visual evaluations are required to find out the subjective preferences for different LED SPDs. In addition, metric(s) that better defines the subjective preferences and colour rendering properties of light sources are needed.

1.2 Objectives of the work

The main objective of this work is to investigate subjective preferences of lighting environments under different LED SPDs and to analyse the different existing colour quality descriptors of lighting to recommend the best descriptor. The subjective preferences are investigated with the help of user acceptance studies in terms of naturalness, colourfulness and the overall preference of lighting environment.

The other objective is to find out the CCT and illuminance level that users prefer for LED lighting.

In addition, the objective is also to investigate the prediction of colour fidelity (colour rendering) provided by different colour fidelity metrics.

2. State of the art

2.1 Colour rendering of light sources

Colour rendering property of light source is one of the important aspects of the colour quality of the light source. The international commission of illumination (CIE) has defined colour rendering as "*Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant*" [3]. The only internationally recognized metric to measure and specify the colour rendering properties of light source is CIE CRI [3]. The CIE CRI has been used for over 40 years and is widely accepted.

The CIE CRI is calculated using the CIE Test Sample method approved by CIE in 1974 [3]. In this method, the tristimulus values of 14 Munsell test colour samples are calculated using the spectral power distributions of the test light source and the reference light source. The reference light source should have the same CCT as the test light source: either a Planckian radiator (CCT< 4999 K) or a daylight distribution (CCT>5000 K). The von Kries transformation is used for chromatic adaptation transform. The colour difference for each sample between the two light sources is calculated in CIE 1964 U*V*W* colour space. The special colour rendering index (Ri) is calculated for each sample by equation (1)

$$R_i = 100 - 4.6\Delta E_i \tag{1}$$

where ΔE_i is the colour difference between the reference and test source of i^{th} colour sample.

The general colour rendering index (Ra) or CIE CRI is then the average of the first eight special colour rendering indices (Ri).

Despite its prominence, the CIE CRI has several shortcomings and problems [4], [6], [7]. In the CIE Test Sample Method, the reference source should be selected either from a blackbody radiator or from a phase of daylight, the only criterion being the correlated colour temperature (CCT). There is nothing apparent that says that Planckian radiators and a phase of daylight are perfect in a colour-rendering sense. The CIE Test Sample Method is based on CIE U*V*W* colour space, which is far from being equidistant and is now outdated [2]. The von Kries chromaticity transformation used by the CIE CRI is also considered obsolete and inadequate. A transformation such as the CIE Chromatic Adaptation Transform (CIE CAT02) [8], performs much better than the von Kries chromaticity transformation. The CIE CRI is the single averaged number of eight special colour rendering indices, and the light sources with the same CIE CRI may render colour differently if they have different special colour rendering indices.

However, the problems of the CIE CRI have become serious enough to require revision of the metric after the emergence of white light from LEDs [5]. Unlike conventional light sources (incandescent and fluorescent lamps), LEDs have greater freedom in spectral design, as white light from LEDs is realized by a mixture of multi-colour LEDs or by a combination of phosphors excited by blue or UV LED emission. By tuning the spectrum of LEDs, high luminous efficacy or high CIE CRI value can be achieved[9]. Only a small shift in the wavelength of one of the LEDs can change the luminous efficacy and colour rendering properties of white LED light sources. However, luminous efficacy and CIE CRI have a trade-off relationship [9], [10]. Many questions have arisen about whether or not the CIE CRI should be considered as a design aspect of white LEDs because of many flaws in the CIE Test Sample Method.

Several visual experiments conducted using white LEDs [11]–[16] have shown that the CIE CRI is not a suitable descriptor of the visual colour rendering of white LED light sources. The limitations of the CIE Test Sample Method to calculate the CIE CRI of white LED light sources have been acknowledged by the CIE. The CIE technical committee (TC 1-62) concluded that the current CIE CRI cannot generally be applied to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in the set [5]. CIE TC 1-62 recommended the development of a new colour rendering index [5]. In 2006, the technical committee CIE TC 1-69 Colour Rendition by White light sources was formed " to investigate new methods for assessing the colour rendition properties by white-light sources used for illumination, including solid-state light sources, with the goal of recommending new assessment procedures." Nine different metrics were proposed to the CIE TC 1-69 (see Publication [II]). It is believed that these metrics cover different aspects of colour quality. However, the TC 1-69 could not make a recommendation of new metrics to replace the CIE CRI.

In September 2012, two new TCs were established: TC 1-90 and TC 1-91. The TC 1-90 was titled '*Colour Fidelity Index*', with terms of reference "to evaluate available indices based on colour fidelity for assessing the colour quality of white light sources with a goal of recommending a single colour fidelity index for industrial use". TC 1-91 was titled '*New Method for Evaluating the Colour Quality of White Light Sources*', with a goal of recommending new methods for industrial use (methods based on colour fidelity should not be included).

The main aim to form the two TC was to distinguish between colour fidelity and colour preference properties (along with naturalness of objects) of light sources. Colour fidelity describes the ability of a light source to render the same colours as a reference illuminant, whereas colour preference describes the aesthetic judgement about the vividness, choice and naturalness of all objects by considering each object separately [17]. The most popular colour fidelity metrics are the CIE CRI [3], the CRI2012 [18], the CRI-CAM02UCS [19], and the colour quality scale (CQS) [20]. Besides these metrics, the metrics like categorical colour rendering (CCRI), CQS, Feeling of contracts index (FCI), Memory colour rendering index (MCRI), Preference index of skin (PS), and Harmony rendering index (HRI) were considered as non-fidelity metrics and were proposed to the CIE TC 1-91.

People's judgement of colour quality in terms of both colour fidelity and colour preference can only be determined with the help of user acceptance studies. Various user-acceptance studies using experimental booths have been conducted to investigate the colour quality (preference, attractiveness, naturalness, or fidelity) of LED light sources [16], [21]–[24] by considering several metrics.

The studies by Narendran *et al* [16], Rea *et al* [21], and Jost-Boissard *et al* [22] found that the CIE CRI has no correlation to peoples' colour preferences. However, Rea *et al* [21] suggested that the high value of CIE CRI and the gamut area index (GAI) (CRI≥80 and 80≤GAI≥100) can ensure positive subjective impressions of naturalness and vividness. Jost-Boissard *et al* [22] performed user acceptance studies in experimental booths and analysed the five different metrics, namely the CIE CRI, Ra1-14, Colour quality scale (CQS), Full-spectrum colour index (FSCI) and GAI. They found that GAI and CQS describe attractiveness and naturalness, respectively, better than do the other metrics. The experiments were conducted using different LED clusters and standard light sources at illuminance level of around 225 lux. Nascimento and Masuda [25] conducted psychophysical experiments in which observers selected illuminants from a set of metamers of D65 to render outdoor and indoor scenes. The scenes were digitalized by hyperspectral imaging. The study showed that CIE CRI is not a good descriptor for naturalness and individual preference. It was also found that the observer preferred the illuminant that produced colours a little more saturated.

Smet *et al* [23] demonstrated that the colour quality of a light source in terms of preference, attractiveness and fidelity is very well correlated with memory colour rendering index (MCRI) and moderately well with vividness and naturalness, compared to the CIE CRI and CQS. Smet *et al* [24] compared the performance of 13 colour quality metrics by using the scaling of the perceived colour quality obtained in several different psychophysical studies. Smet *et al* [26] optimised a LED module based on the MCRI and conducted a psychophysical rating experiment at CCT of 2700 K under incandescent lamp and with 18 observers. Guo and Houser [6] investigated the cross-comparison of several metrics based on simulation. However, they did not conduct a user acceptance study. Ryckaert *et al* [27] tested different types of linear LED tubes and fluorescent lamps in a small office room to find out the one-to-one replacement for a classical fluorescent lamp. They found that the scores for attractiveness and naturalness were in line with the CIE CRI, CQS and MCRI values for two types of LED tubes, whereas, one type of LED tube (i.e. Brand I) showed the opposite scores. On the other hand, a visual experiment performed by Pousset *et al* [28] found that the ranking provided by CQS for the five LED light sources was inconsistent with the visual subjective rankings. The five light sources used had CCTs of 2850K, 3030K, 3500K, 5930K and 6100K. These light sources were compared with each other in a booth at illuminance level of 150 lux.

All of the studies presented above, except the study by Guo and Houser[6] and Ryckaert *et al* [27], were conducted in experimental booths and showed inconsistent results. In booth experiments, observers mainly focus on limited scenes, in which it is difficult to have visual perceptions similar to those found in real working environments. The observers' preferences for particular light sources might change when shifted from a booth to a real environment. For an emerging technology like LED, it is very important to know the subjective preferences in real environments. However, end-users' needs, expectations and preferences for office lighting applications based on LEDs are not well-known. Only few studies[27], [29], [30] using LEDs in office environments to study the colour quality of light sources were found. Ryckaert *et al* [27] studied linear LED lamps versus fluorescent lamps; however, they failed to make clear conclusions, as the illuminances of the LED lighting were almost 50 per cent lower than those of the fluorescent lamp lighting. Lin *et al* [29] and Spaulding *et a*l[30] studied LEDs at different CCTs chosen by considering only the CIE CRI as a colour rendering metric.

The CIE CRI is actually a colour fidelity metric, and it can only define the colour fidelity aspect of colour quality. Visual experiments [15], [31], [32] related to colour fidelity have been conducted to test the CIE Test Method (a method to calculate CIE CRI) and different colour difference formulae. Sándor and Schanda [15] adopted a simultaneous colour matching technique to assess, with the help of ten observers, the colour difference of different colours of the Macbeth Colour checker (MCC) chart. Li *et al* [31] conducted an experiment with eight observers, using a successive colour matching technique. These studies showed that visual colour rendering is not well described by the CIE Test Method and that visual colour difference correlates very well with the CIECAM02 [33] based colour difference formula. Even though Sándor and Schanda [15] and Li *et al* [31] adopted two different techniques for colour matching, they reached the same conclusion. A study conducted by Luo *et al* [32] showed that CQS, nCRI, CRI-CAM02UCS and CIE CRI give similar performance results regarding colour fidelity. The study adopted a successive colour matching (magnitude estimation) technique to assess 22 colours under 19 light sources, and ten observers participated in the study.

2.2 Preference of CCT and illuminance level

Correlated colour temperature (CCT) and light level or illuminance level are the other important characteristic of lighting. The preferences for CCT and illuminance level can vary for different lighting applications. Many visual experiments have been conducted to find out the preference of CCT using FLs [34]–[42]. Schroder [34] studied the effect of CCT on visual comfort and found that observers preferred warm CCT, i.e. 3000 K, over cool CCT at 1000 lux and 500 lux. Wei *et al* [35] found that a lit environment in an office space at 3500 K (at 500 lux) was more comfortable and satisfying than at 5000 K. The study done by Hu *et al* [36] found that observers preferred to work under CCT of 3500 K rather than under CCT of 6500 K. Shamsul *et al* [37] found that a light source with a CCT of 4000K was the most preferred and most comfortable over CCTs of 3000 K and 6500 K. Kang *et al* [38] found that observers preferred a lighting environment at a CCT of 4000K for visual comfort over those at CCTs of 3000K and 6500 K. Park *et al* [39] conducted an experiment in office space at 3000 K, 4000 K, 5000 K and 6000 K and found that 5000 K was suitable CCT for an office space, 4000 K was the most preferred CCT and 3000 K was the most comfortable CCT. Manav [40] studied the appraisal of the visual environment in offices with CCTs of 2700 K and 4000 K. The study showed that 4000 K was preferred over 2700 K for impressions of comfort and spaciousness, while 2700 K was preferred for relaxation. It was also found that objects looked more saturated under 2700 K. Cockram *et al* [41] found, in a field survey, that people preferred a daylight lamp (4300 K) for office work over a FL at 6500 K. Masuda and Nascimento [42] empirically carried out spectral optimization for naturalness and preference in a set of psychophysical experiments. They found that for daylight-like illuminants and their metamers, the most natural colours were produced under illuminants with an average CCT of 6040 K and the most preferred colours with an average CCT of 4410 K.

The Kruithof's curve [43] suggests a relationship between illuminance level and preferred CCT; people prefer low CCTs at low illuminance levels and high CCTs at high illuminance levels. However, Boyce and Cuttle [44] found that CCT had no significant effects on subjective impressions and that the illuminance level determines the impression created by the lighting of the room. They investigated CCT, illuminance and subjective impressions of FL lighting in a room. As the illuminance level increased, the lighting of the room became more pleasant, more natural, more comfortable, more colourful, more warm and more uniform [44]. A visual experiment performed by Schröder [34] using FL found that the illuminance level of 500 lux was significantly more comfortable than 1000 lux at 3000 K, but the results were not significantly different at 6000 K. Viénot *et al* [45] conducted an experiment under LED lighting in a lighting booth to test the predictions of the Kruithof's curve and found that the Kruithof's rule was partly validated. They found no indication that high colour temperature is perceived more pleasant than low colour temperature at high illuminance levels when light sources have high CIE CRI. Manav [40] found that 4000K was preferred to 2700K for impressions of comfort and spaciousness at illuminance levels of 500 lux, 750 lux and 1000 lux.

Overall, there is some support that people prefer 4000 K lighting environment over 6500 K environment when FLs are used. However, the preference of CCT can be different for a lighting environment illuminated by LEDs, as LED SPDs are different from those of fluorescent lamps. Only a few studies [29], [30], [45], [46] have been done under LED lighting in office environments to find out the preference of CCT.

Spaulding *et al* [30] studied four lighting scenes: LED lighting at 3500 K and at 4000 K with Ra = 90, T8 FL lighting at 4100 K (Ra≈85), and T8 FL lighting at 4100 K plus an additional incandescent desk lamp in an office looking booth. They found that the lighting scene with FL at 4100 K with an additional incandescent desk lamp was rated to be the most comfortable and the lighting scene with FL at 4100 K was the most pleasing. Lin *et al* [29] found 4000 K and 7000 K as the most preferred CCT settings for LED office lighting when the light level was set at 600 lux. Huang *et al* [46] studied the effects of CCT (2700 K, 4300 K, and 6500 K) at 500 lux on focused and sustained attention under white LED desk lighting. The result showed that focused and sustained attention was significantly better at 4300 K.

The studies specified above show inconsistent results and give little help to understand the subjective preference of CCT and illuminance level for LED lighting.

3. Subjective preferences of light sources in experimental booths

3.1 Introduction

People's judgement of colour quality can only be determined with the help of user acceptance studies, the most popular methods for which are an individual presentation, a side-by-side presentation and a rapid sequential presentation.

In this work, user acceptance studies based on an individual presentation and a side-by-side presentation in lighting booths were conducted. The aim was to investigate the subjective preferences and colour rendering properties of various LED SPDs compared to conventional FLs (Publication [I, II]). Rapid sequential presentation method was not used because in this method the eyes of the observer do not get fully adapted to separate illuminations [47].

For this study, 21 LED SPDs were optimised at three CCT values; 2700 K, 4000 K and 6500 K by considering three of the metrics proposed to the CIE TC 1-69. These were the CQS gamut area scale, the CQS colour preference scale and the FCI, as well as the CIE CRI. The optimised LED SPDs were realised with a LED simulator and were assessed in a lighting booth by 60 observers.

3.2 Experimental set-up

A lighting booth with three sections (each with the height of 1 m, width of 0.5 m and depth of 0.5 m) was constructed in a dark room. The inner surface of the booth was coated with matt grey paint (IN2-NCS-S2500N) maintaining the surface reflectance at 50 %.

Twenty-one different LED SPDs (seven spectra each at CCTs of 2700 K, 4000 K and 6500 K) and three fluorescent lamp SPDs were used in the experiment (Figure 1).

Altogether 60 observers with normal visual acuity and colour vision participated in the experiment: 20 male and 20 female aged 20-40 years (average age 25.5 for male and 24.6 for females), and 10 male and 10 female aged 50-65 years (average age 56.1 for male and 54.9 for females). The observers were of two ethnic groups: European and Asian. There were 42 European and 18 Asian observers. The Lea Numbers Near Vision chart was used for measuring visual acuity, the value > 6/6 being the limit for normal vision. Colour vision was tested using the Ishihara pseudoisochromatic plates.

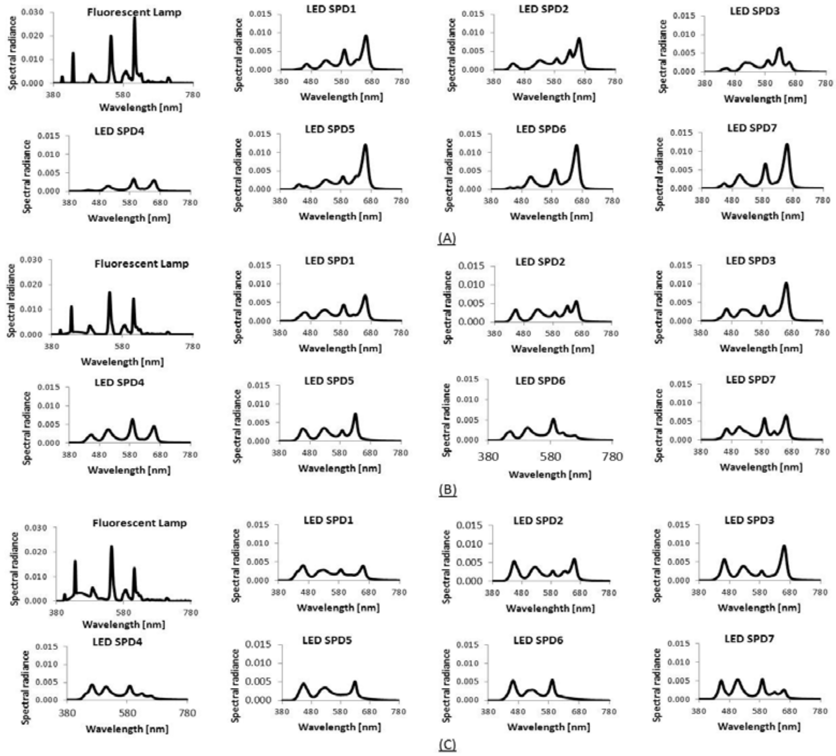

Figure 1. FL and LED SPDs at CCT of: (A) 2700 K, (B) 4000 K and (C) 6500 K

Seven objects related to office environment were selected for the experiments: a coloured picture, a sample of wood, a smartphone, a hand (observer's skin), printed text, a Coke can and a Macbeth Colour checker (MCC) chart (for more details see Publications [I, II]).

The questionnaire used in the experiment had two parts: (i) individual evaluation (Questions 1-4) and (ii) comparison evaluation (Questions 5-6). The individual evaluation referred to viewing a single booth at a time and rating the lit environment in that booth by putting a mark on a continuous line scale in the questionnaire. There were questions related to naturalness of the selected seven objects (Question 1-2), visual appearance (Question 3) and colourfulness of the MCC chart (Question 4). Question 3 related to the visual appearance dealt with brightness (dim/bright), visual comfort (uncomfortable/comfortable), pleasantness (unpleasant/pleasant), and boredom (boring/interesting) of the lit scene in the booth. In the comparison evaluation, the observers compared the naturalness of objects and the overall preferences of the lit scenes under LEDs and FLs.

3.3 Results

To study the effect of the relative positions of light sources (FLs/LEDs) in the observers' judgment, reverse comparison and comparison evaluation was carried out. In the reverse comparison, the observers compared the LED SPD in the left-hand section of the booth with the FL in the middle section of the booth, and, in the comparison evaluation, the observers compared the same LED SPD (used in reverse comparison evaluation) in the right-hand section of the booth with the FL. The results show that the relative positions of the light sources did not affect the judgement of the observers. (Publication [I])

3.3.1 Individual evaluation

The 60 observers evaluated 24 lighting conditions for different questions regarding naturalness of objects (Q1 & Q2), the visual appearance of the lit scene in the booth (Q3), and the colourfulness of the MCC chart (Q4). For statistical analysis, the marked ratings for every question were measured and converted into a range of values between -3 and +3. An ANOVA with the significance level of $p=0.05$ was performed to investigate the statistical significance of the observers' mean ratings for particular questions for different SPDs, irrespective of age group, ethnicity and gender (Appendix C, Publication [II]). Duncan procedure was used as a *post-hoc* analysis.

The results show that the observers preferred LED SPD2, LED SPD5 and FL (at all three CCTs) for most of the questions related to the naturalness of objects, the visual conditions in the lit environment and the colourfulness of MCC chart (Table 1). The LED SPD4 and LED SPD6 were the least preferred (for the same questions).

Preference of CCTs

The differences in the observers' mean ratings at three CCTs were statistically significant for the overall naturalness of all objects, naturalness of the Coke can, naturalness of printed text, bright/dim and interesting/boring for different SPDs. CCT of 2700 K was the least preferred for the naturalness of objects.

For the question uncomfortable/comfortable and unpleasant/pleasant about the lit environment, the observers' mean rating at 4000 K was statistically higher than at CCT 2700 K. The differences in the means of the observers' ratings were statistically significant for the question dark/bright about the MCC. The observers preferred CCT 4000 K and CCT 6500 K to CCT 2700 K.

3.3.2 Comparison Evaluation

The comparison evaluation data were converted into a frequency form by counting the number of observers who chose the FL or the LED SPDs for each object. There were 60 responses for each object in one lighting condition. The experimental data were ordinal and therefore required a non-parametric method for statistical significance testing. Hence, the chi-square test, the most widely used method for testing frequency data, was selected. The chi-square test measures the divergence of the observed data from expected values under the null hypothesis of no association. The summary of statistical analysis for comparison evaluation results at 2700 K, 4000 K, and 6500 K are shown in Table 2.

Table 1. The mean observer ratings for different questions and different SPDs

CCT		SPD1	SPD2	SPD3	SPD4	SPD5	SPD6	SPD7	FL	p-value
	Mean ratings for question about naturalness of objects									
	Q 1	*0.68*	**1.28**	*0.59*	*0.48*	**1.33**	*0.61*	**1.56***	**1.37**	**<0.001**
	Q 2.1	0.81	**1.19**	*0.66*	*0.51*	**1.09**	*0.58*	**1.24***	1.04	**0.016**
	Q2.2**	1.01	1.26	0.94	0.98	1.43	1.06	1.44	1.44	0.065
	Q 2.3	*0.58*	**1.22**	*0.51*	*0.21*	**1.02**	*0.51*	**1.27***	**1.15**	**<0.001**
	Q 2.4	*0.71*	**1.18**	*0.65*	*0.38*	**1.21**	*0.83*	**1.45***	**1.04**	**0.001**
	Q 2.5	*0.91*	**1.40**	1.01	*0.86*	**1.50***	*0.80*	1.27	1.30	**0.017**
2700 K	Q 2.6	*0.73*	**1.29**	*0.77*	*0.53*	**1.24**	*0.54*	**1.54***	**1.51**	**<0.001**
	Mean ratings for questions about visual appearance of the lit environment									
	Q 3.1	0.43	**1.40***	0.65	*-0.16*	0.79	*0.23*	**1.01**	0.76	**<0.001**
	Q 3.2	*0.65*	**1.38***	*0.62*	*0.27*	**1.20**	*0.41*	**1.15**	**1.19**	**<0.001**
	Q 3.3	*0.70*	**1.29***	*0.60*	*0.28*	**1.06**	*0.32*	**1.08**	**1.14**	**<0.001**
	Q 3.4	*0.41*	**1.09***	*0.43*	*0.09*	**0.68**	*0.19*	**0.70**	**0.70**	**<0.001**
	Mean ratings for questions about colourfulness of MCC									
	Q 4.1	0.29	**1,30***	0,44	*-0,27*	**0,94**	0,27	**0,80**	**0,85**	**<0,001**
	Q 4.2	0,97	**1,74***	1,05	*0,16*	**1,64**	0,76	**1,34**	**1,29**	**<0,001**
	Mean ratings for question about naturalness of objects									
	Q 1	**1,43**	**1,39**	*1,11*	*0,85*	*1,26*	*1,18*	*0,96*	**1,77***	**0,005**
	Q 2.1	**1,16**	**1,11**	*0,33*	*0,52*	0,86	0,91	*0,29*	**1,57***	**<0,001**
	Q2.2**	1,37	1,25	1,17	1,36	1,55	1,39	1,15	1,66	0,252
	Q2.3**	1,05	1,07	0,70	0,55	0,92	0,85	0.66	1.26	0.101
	Q 2.4	**1.27**	**1.23**	1.14	*0.68*	**1.30**	*1.01*	1.07	**1.59***	0.025
	Q2.5**	1.39	1.48	1.20	1.10	1.24	1.19	0.92	1.39	0.271
4000 K	Q2.6**	1.47	1.48	1.10	1.28	1.37	1.36	0.97	1.57	0.162
	Mean ratings for questions about visual appearance of the lit environment									
	Q 3.1	1.14	**1.65***	*0.87*	*0.55*	**1.53**	*0.69*	*0.72*	**1.52**	**<0.001**
	Q 3.2	**1.38**	**1.37**	*0.80*	*0.68*	1.14	*0.95*	*0.93*	**1.51***	**0.001**
	Q 3.3	**1.28**	**1.38**	*0.77*	*0.52*	**1.12**	0.95	*0.79*	**1.43***	**<0.001**
	Q 3.4	**0.92**	**1.22***	*0.48*	*0.20*	**0.97**	*0.46*	*0.42*	**1.16**	**<0.001**
	Mean ratings for questions about colourfulness of MCC									
	Q 4.1	0.89	**1.70***	0.85	*0.24*	**1.32**	*0.50*	*0.52*	**1.50**	**<0.001**
	Q 4.2	1.23	**1.78***	1.19	*0.52*	**1.78***	*0.69*	*0.95*	**1.61**	**<0.001**
	Mean ratings for question about naturalness of objects									
	Q 1	**1.18**	**1.18**	**1.24**	*0.87*	**1.39**	*0.43*	**1.13**	**1.68***	**<0.001**
	Q 2.1	**1.06**	**1.10**	0.77	0.67	**1.25**	*-0.17*	0.73	**1.45***	**<0.001**
	Q2.2**	1.33	1.28	1.22	1.36	1.42	0.98	1.50	1.65	0.114
	Q 2.3	**0.82**	**1.16**	**0.96**	**0.75**	**1.11**	*0.21*	**0.74**	**1.26***	**0.002**
	Q 2.4	**1.33**	**1.22**	**1.20**	0.92	**1.33**	*0.26*	**1.08**	**1.57***	**<0.001**
	Q2.5**	1.24	1.31	1.22	1.03	1.50	0.97	1.08	1.33	0.33
6500 K	Q 2.6	1.52	1.22	*1.12*	1.41	**1.71***	*1.05*	1.31	**1.66**	**0.02**
	Mean ratings for questions about visual appearance of the lit environment									
	Q 3.1	1.23	**1.74***	1.20	*0.65*	**1.63**	*0.65*	*0.91*	**1.48**	**<0.001**
	Q 3.2	0.94	0.93	1.02	*0.74*	**1.32**	*0.54*	*0.78*	**1.40***	0.006
	Q 3.3	**1.02**	**0.89**	**1.06**	*0.62*	**1.28**	*0.25*	*0.67*	**1.41***	**<0.001**
	Q 3.4	**0.73**	**0.97**	**0.98**	*0.45*	**1.08***	*0.24*	*0.42*	**1.08***	**<0.001**
	Mean ratings for questions about colourfulness of MCC									
	Q 4.1	0.95	**1.53***	**1.07**	*0.61*	**1.52**	*0.40*	*0.76*	**1.40**	**<0.001**
	Q 4.2	1.16	**1.71***	**1.48**	0.70	**1.55**	*0.20*	0.90	**1.29**	**<0.001**

SPD1 to SPD7 are LED spectra and SPD8 is fluorescent lamp SPD

** The mean ratings for these questions were not statistically significant (at 0.05 significance level) for different SPDs.

Bold= the mean values for the SPDs which were in the group with the highest mean value in Duncan test.

Bold*= the mean ratings which were highest among the mean ratings for a particular question.

italic= the mean ratings for the SPDs which were in the group with the lowest mean value in Duncan test.

Table 2. The number of observers (out of 60) who considered each object more natural in appearance under the LED lamp (LED) when compared to the fluorescent lamp (FL) and had a preference for the LED lamp over the FL lamp when both are at (a) 2700 K (b) 4000 K and (c) 6500 K. Comparisons where there is a statistically significant difference between the LED and the FL lamp are shown in bold together with the associated p value.

(a)

CCT 2700 K	FL vs LED SPD1		FL vs LED SPD2		FL vs LED SPD3		FL vs LED SPD4		FL vs LED SPD5		FL vs LED SPD6		FL vs LED SPD7	
	LED SPD1	p-value	LED SPD2	p-value	LED SPD3	p-value	LED SPD4	p-value	LED SPD5	p-value	LED SPD6	p-value	LED SPD7	p-value
Hand	**19**	**0.005**	**38**	**0.039**	25	0.241	**20**	**0.01**	**39**	**0.02**	23	0.071	37	0.071
Mobile	**19**	**0.006**	**42**	**0.002**	24	0.121	**17**	**0.001**	**47**	**<0.001**	**19**	**0.009**	**43**	**0.001**
Picture	23	0.071	33	0.439	27	0.515	23	0.071	33	0.439	**22**	**0.039**	33	0.439
Coke can	23	0.071	**43**	**0.001**	28	0.606	**17**	**0.001**	**45**	**<0.001**	28	0.606	**43**	**0.001**
Printed text	**18**	**0.002**	42	**0.002**	25	0.197	26	0.302	**45**	**<0.001**	**20**	**0.01**	32	0.606
Sample of Wood	**5**	**<0.001**	40	**0.01**	**12**	**<0.001**	**10**	**<0.001**	**44**	**<0.001**	**14**	**<0.001**	35	0.197
MCC chart	**13**	**<0.001**	44	**<0.001**	23	0.071	**16**	**<0.001**	**40**	**0.01**	24	0.121	37	0.071
Preference	**12**	**<0.001**	43	**0.001**	**21**	**0.02**	**12**	**<0.001**	**49**	**<0.001**	**18**	**0.002**	**41**	**0.005**

(b)

CCT 4000 K	FL vs LED SPD1		FL vs LED SPD2		FL vs LED SPD3		FL vs LED SPD4		FL vs LED SPD5		FL vs LED SPD6		FL vs LED SPD7	
	LED SPD1	p-value	LED SPD2	p-value	LED SPD3	p-value	LED SPD4	p-value	LED SPD5	p-value	LED SPD6	p-value	LED SPD7	p-value
Hand	25	0.197	28	0.606	**19**	**0.005**	**22**	**0.039**	**16**	**<0.001**	**18**	**0.002**	24	0.121
Mobile	25	0.197	37	0.071	**22**	**0.039**	24	0.121	36	0.121	29	0.796	29	0.796
Picture	35	0.197	34	0.302	25	0.197	23	0.071	28	0.606	25	0.197	27	0.439
Coke can	27	0.439	**38**	**0.039**	31	0.796	**15**	**<0.001**	**38**	**0.039**	**16**	**<0.001**	26	0.302
Printed text	33	0.439	34	0.302	27	0.439	30	1.000	30	1.000	28	0.606	25	0.197
Sample of Wood	28	0.606	33	0.439	**21**	**0.020**	24	0.121	32	0.606	26	0.302	25	0.197
MCC chart	26	0.302	36	0.121	30	1.000	**16**	**<0.001**	**38**	**0.039**	**17**	**0.001**	23	0.071
Preference	34	0.302	37	0.071	23	0.071	**17**	**0.001**	33	0.439	**22**	**0.039**	**22**	**0.039**

(c)

CCT 6500K	FL vs LED SPD1		FL vs LED SPD2		FL vs LED SPD3		FL vs LED SPD4		FL vs LED SPD5		FL vs LED SPD6		FL vs LED SPD7	
	LED SPD1	p-value	LED SPD2	p-value	LED SPD3	p-value	LED SPD4	p-value	LED SPD5	p-value	LED SPD6	p-value	LED SPD7	p-value
Hand	24	0.121	23	0.071	**19**	**0.005**	27	0.439	26	0.302	**9**	**<0.001**	**18**	**0.002**
Mobile	31	0.796	31	0.796	33	0.439	30	1.000	**40**	**0.010**	**21**	**0.020**	**28**	0.606
Picture	**38**	**0.039**	**41**	**0.005**	**39**	**0.020**	33	0.439	36	0.121	**18**	**0.002**	26	0.302
Coke can	33	0.439	**42**	**0.002**	37	0.071	25	0.197	**40**	**0.010**	**10**	**<0.001**	**22**	**0.039**
Printed text	36	0.121	33	0.439	33	0.439	30	1.000	33	0.439	29	0.796	27	0.439
Sample of Wood	32	0.606	28	0.606	**20**	**0.010**	28	0.606	30	1.000	**20**	**0.010**	32	0.606
MCC chart	31	0.796	**46**	**<0.001**	36	0.121	26	0.302	**38**	**0.039**	**12**	**<0.001**	**18**	**0.002**
Preference	32	0.606	**40**	**0.010**	33	0.439	27	0.439	**41**	**0.005**	**12**	**<0.001**	23	0.071

The comparison evaluation results show that a larger number of the observers preferred the FL (for naturalness as well as overall preference) to the LED SPD1, the LED SPD4, and the LED SPD6 at all three CCTs (Publication [I] Table 4-5) , and the most of the differences in the evaluations were statistically significant (Table 2). In contrast, the LED SPD2 and the LED SPD5 were more preferred by the observers than the FL at all CCTs (Table 2).

In the comparisons between the FL and the LED SPD3, the results show that a larger number of the observers preferred the FL to the LED SPD3 at 2700 K and 4000 K. However, at 6500 K the LED SPD3 was preferred. Similarly, a larger number of observers prefer the LED SPD7 at 2700 K rather than the FL: however, the contrary is true at 4000 K and 6500 K.

3.4 Summary

The subjective preferences in terms of naturalness, pleasantness, comfort, brightness, colourfulness and overall preference of the lit environment were studied in lighting booths by using individual and comparison evaluations.

The results of the individual and comparison evaluation showed that, when the objects looked more natural and more colourful in the booth under particular SPDs, the observers found these lit environments visually brighter, more comfortable and more pleasing under those SPDs. The results also showed that the observers preferred LED SPDs (i.e. LED SPD2 and LED SPD5 at all CCTs) which have high CQS Qg and CQS Qp values. On the other hand, LED SPDs that have comparatively low values of CQS Qp and CQS Qg (i.e. LED SPD4 and LED SPD6) at all CCTs were least preferred.

The statistical analysis for CCT preference showed that observers preferred higher CCT (4000 K/6500 K) over lower CCT (2700 K). The lighting environment under the CCT 4000K was found to be more comfortable and more pleasing, whereas the environment under the CCT of 6500K was found to be brighter than under other CCTs.

It was also found that the gender of the observers did not affect the rating in either of the evaluations. In the individual evaluation, significant differences were found between the mean ratings of the two ethnic groups (Asian and European), and no difference was found between two age groups (20-40 and 50-65 years old). The mean ratings of European observers were significantly higher than those of Asian observers for all question. However, the contrary was true in the comparison evaluation.

4. Optimization of LED SPDs for luminous efficiency and cost

The studies presented in Section 3 indicate that the LED SPD which have high values of colour quality scale (CQS) colour preference scale (Qp) and CQS colour gamut area scale (Qg) are the most preferred by the observers. These LED SPDs were realized with a 12-channel LED simulator. The LED simulator consists of a LED panel, a PC DMX/RDM USB Interface and a power supply unit. The LED panel of the LED simulator has 12 independent strings of different types of LEDs, and each string has nine LEDs connected in series. This system will probably not be commercially exploitable due to its complexity. The problem of this light source is that different LEDs have different temperature behaviour characteristics. Hence, the light outputs of the different LEDs change unequally with varying ambient/junction temperature, resulting in a change of the chromaticity point of the light output. This could be compensated by active measurement via optical sensors; however, it would result in further complexity and higher costs in a situation where there are large numbers of LEDs. Therefore, a commercially successful solution requires a significant reduction in the types of LEDs used. A favourable solution would be to use either one blue LED with one or two phosphors or one LED with one phosphor and one additional LED.

The purpose of the work (Publication [III]) was to study the possibility of generating simplified LED SPDs having CQS Qp and CQS Qg values similar to those of the preferred complex LED SPDs found in the previous user-acceptance studies (Publications [I, II]).

4.1 Optimizing the preferred LED spectra by simulation

4.1.1 The simulation software

The simulation software employed is proprietary software from OSRAM OS, Regensburg, Germany. It is used to simulate the combination of different-coloured LEDs and a phosphor via ray tracing. In the simulation software, an InGaN LED chip with different types of phosphors is used to generate the target SPD. Various-coloured LEDs may also be added if the target SPD cannot be generated by using only the InGaN chip and the phosphors. The input parameters for the coloured LEDs in the software were the dominant wavelength, duty cycle, chip temperature, driving current, forward voltage, and luminous efficiency of radiation (LER).

4.1.2 Preferred SPD derived from lighting booth studies

One of the preferred LED SPDs at 4000 K found in the lighting booths experiment (Publications [I, II]) is illustrated in Figure 2. Hereafter, this SPD is referred to as the “Aalto SPD”. The Aalto SPD has high values of CQS Qp and CQS Qg. The detailed colour characteristics of the Aalto SPD are presented in Table 1.

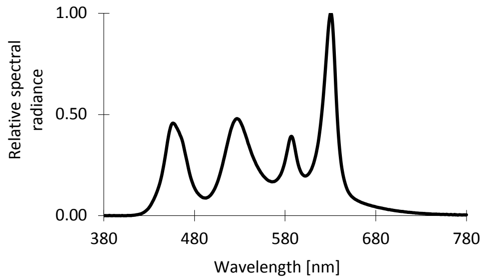

Figure 2. The preferred LED SPD (Publications [I, II]), called the Aalto SPD

4.1.3 Optimization for generating the Aalto SPD

The Osram simulation software was used to generate a number of simplified LED SPDs having CQS Qp and CQS Qg values similar to those of the Aalto SPD. Five of the most general trial SPD configurations are presented in Figure 3. The colour characteristics of the five trial LED SPDs and the Aalto SPD are presented in Table 3.

Table 3. Colour characteristics of the Aalto SPD and different trial LED SPDs

	Aalto SPD	First trial LED SPD	Second trial LED SPD	Third trial LED SPD	Fourth trial LED SPD	Fifth trial LED SPD
CCT (K)	4153	3970	4000	3978	4048	4000
Duv	-0.0050	-0.0014	-0.0007	-0.0005	-0.0042	-0.0041
CIE CRI (Ra)	80	77	94	85	74	96
LER (lm/w)	308	275	280	325	327	319
CQS, (Qa v7.5)	90	89	94	89	84	92
CQS Colour preference scale, (CQS Qp, v7.5)	**101**	**102**	**97**	**94**	**98**	**95**
CQS gamut area scale, (CQS Qg, v7.5)	**114**	**117**	**103**	**107**	**118**	**104**
Feeling of contracts index (FCI)	144	144	117	125	139	123

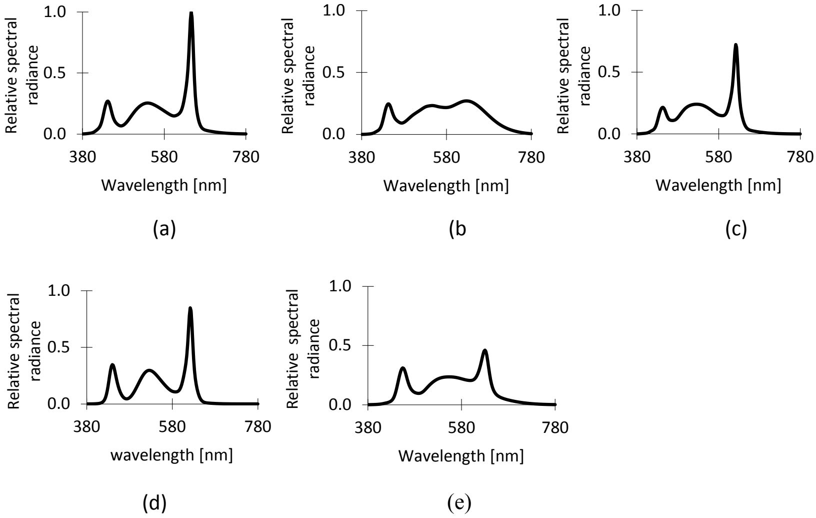

Figure 3. Simulated LED SPDs using Osram-simulation software. (a) first trial, (b) second trial, (c) third trial, (d) fourth trial and (e) fifth trial

Table 3 shows that the first trial LED SPD and the fourth trial SPD are the closest SPDs to the Aalto SPD. The first trial LED SPD was generated with 8.62 wt % (weight percent) of phosphor 1, 53.05 wt % of phosphor 2 and 0.14 wt % of phosphor 3 on an InGaN chip along with a red monochromatic LED of dominant wavelength of 635 nm.

The CQS Qp, CQS Qg and Feeling of Contrast Index (FCI) values of the first trial LED SPD are similar to those of the Aalto SPD. However, the luminous efficacy of radiation (LER) of the first trial LED SPD is lower than that of the Aalto SPD.

The fourth trial was based on an InGaN chip with 48.81 wt % of phosphor 5 and an amber LED with a dominant wavelength of 615 nm. The fourth trial LED SPD is shown in Figure 3 (d). The LER value was higher (327 lm/w) than that of the Aalto SPD (308 lm/w), and the CQS Qp, CQS Qg, and the FCI values were close to those of the Aalto SPD. However, the CIE CRI value was lower than that for the Aalto SPD.

The simulation results suggested that it is possible to generate simplified LED SPDs which have CQS Qp and CQS Qg values similar to those of the preferred complex LED SPDs, without sacrificing LER. However, user acceptance studies are needed to find out the subjective preferences for the simplified LED SPD compared to the preferred complex LED SPDs.

4.2 User acceptance studies

User acceptance studies (Publication [III]) were carried out to investigate the subjective preferences of the lit environment under the simplified LED SPD in comparison with the preferred complex LED SPDs found out in the lighting booth experiments. The simplified LED SPD (called as SPD1) was realized with three different types of LEDs, whereas the preferred complex LED SPD was realised with nine different types of LEDs (Figure 4). It would have been better if the best approximation trial SPD had been used as a test SPD in the user-acceptance studies. However, the best approximation trial SPD could not be used, as it was not economically viable to manufacture the same simulated LED just for testing the user preferences. Moreover, it was not possible to generate simplified SPD at 4000 K due to limitations of the LEDs in the available LED panel. However, a simplified LED SPD could be generated at 2700 K. Hence, the user acceptance studies using side-by-side comparison were conducted at 2700 K instead of 4000 K by comparing the simplified LED SPD (2700 K) with the preferred complex LED SPD, i.e. LED SPD2 (2700 K) (Publications [I, II]) as a reference SPD.

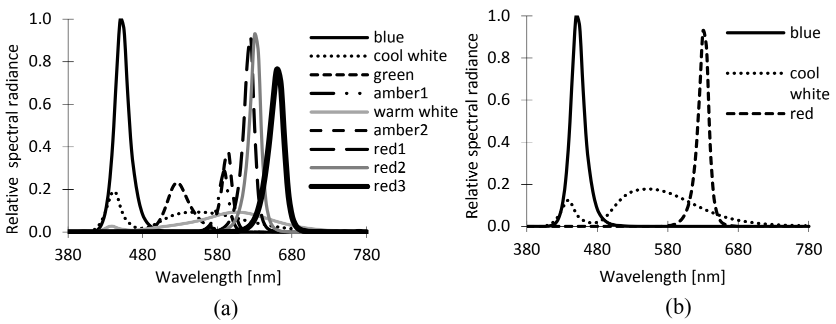

Figure 4. Individual LED SPDs used to realize (a) reference SPD, (b) SPD1 (test SPD)

4.2.1 Experimental set-up

A lighting booth with two identical sections, each section with the height of 1m, width 0.5 m and depth 0.5 m, was constructed in a dark room. One section of the booth was illuminated by a reference SPD and the other section by test SPD.

Forty observers aged 20-30 years (mean 24.15 years, standard deviation 2.64 years) took part in the experiment. In the experiment, natural fruits (a green apple, a tomato, an orange, and a lemon), observer’s own hands and a Macbeth Colour Checker (MCC) chart were used as test objects.

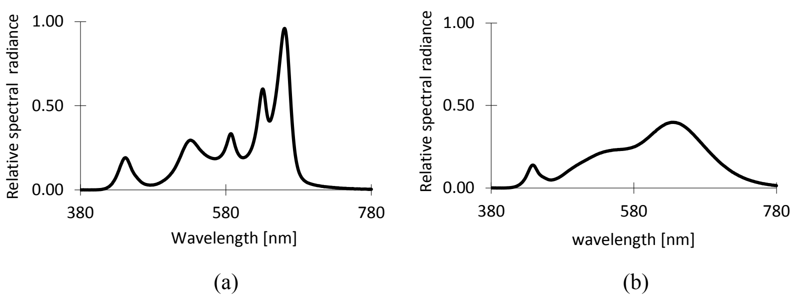

Figure 5. LED SPDs used in the experiment: (a) reference SPD and (b) SPD1 (test SPD)

The questions used in the experiments were related to the naturalness of the fruits and the observers’ hands, the colourfulness of the MCC chart colours and fruits, brightness, and overall preference of the lit environment inside the booth under the test SPDs in comparison with under the reference SPD. The rating scale of the questions in the questionnaire was a seven-point (-3 to +3) scale.

The photometric and colorimetric characteristics of the SPDs used in the experiment are shown in Table 4.

Table 4. Photometric and colorimetric characteristics of the SPDs used in the experiment

	Reference SPD	SPD1
CCT	2803	2794
Duv	-0.0050	-0.0048
CIE CRI	82	86
CQS v7.5	86	86
CQS colour preference scale, (CQS Qp, v7.5)	100	98
CQS gamut area scale, (CQS Qg, v7.5)	119	114
FCI	152	142
GAI	72	69
LER (lm/w)	256	322
Average horizontal illuminance (lux)	458	446

4.2.2 Results

The results of the comparison evaluation between the SPD1 and the reference SPD are shown in Figure 6. The results indicate that the naturalness of lemon and observer's hands as well as the brightness of the lit environment inside the booth are rated significantly higher (tested using one sample t-test) under the SPD1 than under the reference SPD. However, the observers' mean ratings for the colourfulness of the MCC as well as the colourfulness of objects under the reference SPD were significantly higher than under the SPD1. The difference in the mean ratings between the SPD1 and the reference SPD for the naturalness of apple, tomato and orange were not statistically significant.

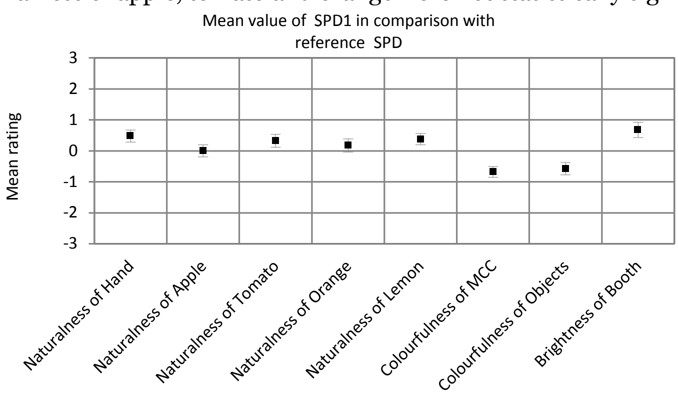

Figure 6. The results of a comparison evaluation between the SPD1 and the reference SPD. The negative mean value indicates that the reference SPD was preferred over the SPD1, whereas positive mean indicates the SPD1 was preferred over reference SPD. Error bars represent ± one standard error of the mean.

The difference in the overall preference for the lit scene inside the booth illuminated by the SPD1 and the reference SPD was not statistically significant when tested using a Pearson chi-square test ($p \leq 0.05$). A Pearson chi-square test was performed, as the comparison evaluation data was collected and converted into a frequency form by counting the number of observers who chose the reference SPD or SPD1.

4.3 Summary

The simulation results suggested that it is possible to generate simplified LED SPDs which have CQS Qp and CQS Qg values similar to those of the preferred complex LED SPDs (Publications [I, II]) without sacrificing luminous efficacy of radiation (LER). User acceptance studies also indicated that the simplified LED, being more efficient, cost effective, and simpler, could provide colour quality characteristics similar or better than the preferred complex LED SPDs.

5. Subjective preferences for light sources in office rooms

5.1 Introduction

Visual perceptions in lighting booths might be different from those in real environment, as in a lighting booth the observer mainly focuses on limited scenes. The observer's preferences for particular light sources might change when the observer is shifted from the lighting booth to a real environment. LED light sources have greater flexibility in spectral design than conventional light sources, offering more dynamic and flexible ways to change the light source chromaticity and colour quality for a wide range of lighting applications. However, end-users' needs, expectations and preferences for office lighting applications based on LEDs are not well known.

Hence, further user acceptance studies in two mock-up office rooms were conducted (Publications [IV, V]). One room was illuminated with LEDs and the other one with fluorescent lamps. For this study, six LED SPDs were optimised at two CCT values (4000 K and 6500 K) by considering three metrics; Qg, Qp and the FCI as well as the CIE CRI. In addition, two light levels, namely 500 lux and 300 lux, were considered for the study. There were forty observers took part in the experiment where they were totally immersed in the lit environment, spent time in the room, performed office-related tasks and evaluated the lit environments. The observers rated the visual appearance (naturalness and colourfulness) of the view seen when sitting at the desk/meeting table, as well as the pleasantness, comfort, attractiveness and preference for the lit environment in the entire room. The objective was to verify the results of the small-scale experiments, to further study peoples' preferences for LED office lighting and to determine the preferred optimum light source SPDs, CCTs and light levels for office environments.

5.2 Experimental set-up

Two office rooms with a surface area of 14.5 m^2 (length 4.20 m, width 3.45 and height 2.45 m) were identically equipped and furnished for the experiments.

Figure 7. Full-scale experiment room from two directions

Ceiling-recessed luminaires with the dimensions of 0.57 m × 0.57 m each were designed to illuminate each room. One room was illuminated with six LED luminaires and another one with six fluorescent lamp luminaires. Eight T5 fluorescent lamps were installed in each FL luminaire: four LUMILUX T5 HO 24 W/840 (4000 K) lamps and four LUMILUX T5 HO 24 W/865 (6500 K) lamps. The lamps of identical CCT were driven by one DALI dimmable Electronic Control Gear (ECG) (Osram QTi DALI 4x14/24 DIM), enabling each CCT to be controlled by two ECGs. The six fluorescent luminaires were connected to a DALI bus, thus making it possible, with a PC, to dim and switch the luminaires to change the illuminance and CCT.

The LED luminaires were built with the help of a LED-based SPD simulator system. The LED panel of the LED simulator had 20 different LED types (with 20 different peak wavelengths) and 24 LEDs per LED type (with the same peak wavelength). The LED panels in the LED luminaires and the lamps in the fluorescent luminaire were concealed by Plexiglas GS WHO2 diffusers in order to get homogeneous illumination in the room. All six LED luminaires were controlled by the PC DMX/RDM USB Interface software.

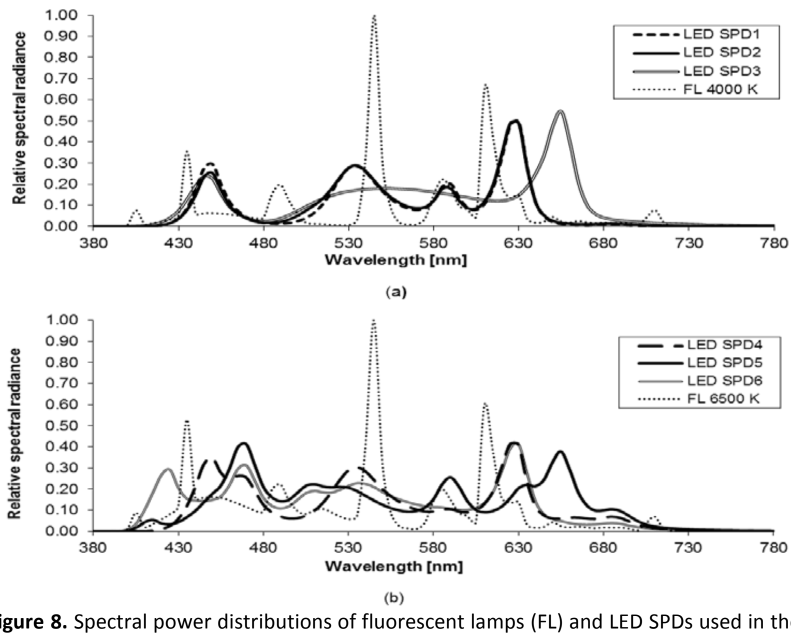

Figure 8. Spectral power distributions of fluorescent lamps (FL) and LED SPDs used in the full-scale experiment (a) at 4000 K and (b) at 6500 K

In the room with the fluorescent luminaires, there were altogether four lighting scenes (two CCTs, two illuminance levels), whereas, in the room with LED lighting, there were altogether 12 lighting scenes (two CCTs, three SPDs, two illuminance levels) to be investigated. The two CCTs and illuminance levels were, respectively, 4000 K and 6500 K, and 300 lux and 500 lux. The LED SPDs used were selected based on the lighting booth investigations. The photometric and colorimetric characteristics of the six LED SPDs and the two FL SPDs are presented in Table 5 and Table 6. The average horizontal illuminance on the working plane (i.e. 0.7 m above the floor) in both rooms under the different lighting settings was maintained at 535±10 lux and at 325±5 lux for the two light levels.

Table 5. Photometric and colorimetric characteristics of the light sources at 500 lux

CCT		x	y	CCT[K] (measured)	Chromaticity difference (Duv)	Average illuminances at work place (i.e. at the height of 0.7m above the floor), lux		
						Desk	Meeting table	Overall room
4000 K	LED SPD1 (high Qp and Qg. Duv=-ve)	0.3739	0.3638	4089	-0.0042	509	552	543
	LED SPD2 (high Qp and Qg. Duv=+ve)	0.3789	0.3835	4089	0.0036	502	543	536
	LED SPD3 (simplest spd, using Red (658 nm), Mint (639 nm) and Blue (448 nm) LEDs)	0.3771	0.3678	4026	-0.0033	498	544	535
	FL	0.3923	0.3914	3800	0.0047	512	554	549
6500 K	LED SPD4 (high Qp and Qg. Duv=-ve)	0.3129	0.3345	6326	-0.0029	502	542	535
	LED SPD5 (medium FCI. low Qp. low Qg)	0.3167	0.3228	6325	-0.0021	509	546	539
	LED SPD6 (medium FCI. high Qp. high Qg)	0.3161	0.3186	6391	-0.004	500	544	532
	FL	0.3127	0.3340	6025	0.0047	515	553	548

Table 6. Colour characteristics of the light sources used in the study

Light source	CCT[K]	Duv	Ra	R9	CQS v7.5	CQS v9.2	Qp v7.5	Qg v7.5	GAI	FCI
LED SPD1	4089	-0.0042	79	56	84	83	98	117	100	145
LED SPD2	4089	0.0036	80	58	86	87	97	113	90	141
LED SPD3	4026	-0.0033	82	48	86	85	96	111	91	132
FL 4000 K	3800	0.0047	81	7	80	81	80	96	71	105
LED SPD4	6326	-0.0029	79	-3	87	87	99	115	117	135
LED SPD5	6325	-0.0021	79	4	85	85	92	107	106	118
LED SPD6	6391	-0.004	80	-1	91	91	101	114	116	124
FL 6500 K	6025	0.0047	85	40	85	86	88	100	98	99

Altogether 40 observers with normal vision participated in the experiment. The subjects represented two age groups: 10 male and 10 female aged 20-30 years, and 10 male and 10 female aged 50-60 years. There were 30 European (10 aged 20-30 years old) and 10 Asian observers.

The questionnaire used in the experiment included five sets of questions to evaluate different aspects of office lighting, such as brightness, amount of light, glare, colourfulness and naturalness of the objects, pleasantness, comfort, and overall preference.

The sets of questionnaire were used to evaluate:

1. The visual performance task on the computer screen;
2. The visual appearance on the desk;
3. The reading task at the meeting table;
4. The visual appearance on the meeting table; and
5. The general room lighting

Seven-point scales were used to record the ratings of the observers for each question. The right end of the seven-point scale was labelled with terms related to the most positive response, and the left end with the most negative response. The middle point indicated a neutral response.

In this work, the second and fourth sets of questions as well as part of the fifth set were considered for evaluating different lighting conditions (Publication [IV]).

5.3 Results

For the analysis, the observers' rating were converted into numerical values on a seven-point scale between -3 and +3; +3 representing an extremely positive response, -3 representing an extremely negative response and "0" representing a neutral response (neither positive nor negative). The four components or scales were derived from the 14 questions: five questions each from the visual appearance on the desk and the visual appearance on the meeting table, and four questions from the general room lighting. Principle components analysis with Varimax rotation was used to identify a simple structure (i.e. four scales). The 14 questions loading higher than 0.5 were interpreted for each of the four components identified as Preference, Naturalness of objects, Naturalness of the hand and Colourfulness (Table 7). The internal consistency reliabilities were good, with Cronbach's alpha ranging from 0.95 to 0.88. The same four scales were obtained when the data were separated as the same CCT or the same light level. The results obtained from the experiment were analysed using the Multivariate analysis of variance (MANOVA) or Analysis of variance (ANOVA), wherever they were applicable.

Table 7. Rotated component loadings for 13 questions

	Preference	Naturalness of objects	Colourfulness	Naturalness of hand
Visual appearance on the desk				
Under the lighting the overall desk area appears to be (Very unpleasant/Very pleasant)	0.738			
The colour of the objects on the desk looks (Very unnatural/Very natural)		0.682		
The colour of the objects on the desk looks (Colourless/Colourful)			0.848	
The colour of the wooden desk surface looks (Very unnatural/Very natural)		0.835		
In this lighting, the colour of my hand looks (Very unnatural / Very natural)				0.810
Visual appearance on the meeting table				
Under the lighting, the overall desk area appears to be (Very unpleasant/Very pleasant)	0.71			
The colour of the objects on the desk looks (Very unnatural/Very natural)		0.67		
The colour of the objects on the desk looks (Colourless/Colourful)			0.84	
The colour of the wooden desk surface looks (Very unnatural/Very natural)		0.78		
In this lighting, the colour of my hand looks (Very unnatural / Very natural)				0.77
General room lighting				
The overall room appearance under this lighting is (Very unpleasant/Very pleasant)	0.81			
Overall, the lighting in the room is (Very uncomfortable/Very comfortable)	0.84			
The lighting makes the room look (Very unattractive /Very attractive)	0.84			
I would prefer the lighting of my working place to be like this (Not at all / Very much)	0.82			
% Variance Explained	32.98	22.22	15.4	13.14
Cronbach's alpha	0.96	0.89	0.88	0.88
Note: Only loadings above a 0.5 criterion are shown.				

5.3.1 Statistical analysis for different SPDs and light levels

The results were examined using a 4 x 2 (SPD x light level) MANOVA for each CCT, with the four scales as dependent variables irrespective of age group, ethnicity and gender. There were no statistically significant interactions between the SPDs and light level at each CCT. Only the main effects of SPDs and light levels were found statistically significant. All the four scale scores were significantly higher at 500 lux than at 300 lux for both CCTs (Figure 10). A post hoc test showed that the scores for different lighting environments under LED SPDs at 4000 K (i.e. LED SPD1 to SPD3) were significantly higher than those under FL at 4000 K, regarding the preference and colourfulness scales. However, there were no statistically significant effects of different SPDs at 4000 K on the naturalness of objects and naturalness of hand (Figure 11). Also, there were no statistically significant differences in the scores for the four scales under different SPDs at 6500 K (Figure 12).

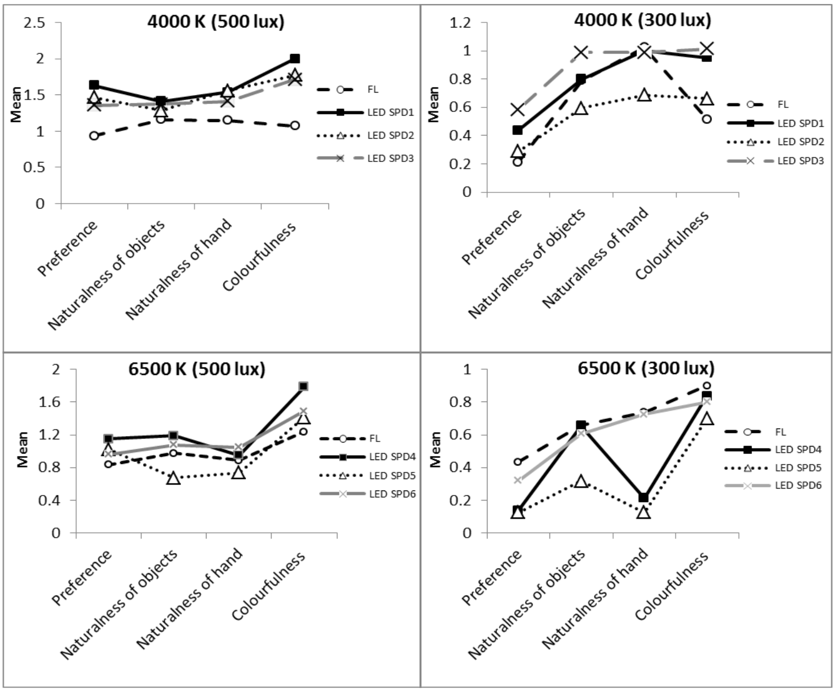

Figure 9. The mean scores for the four scales (preference, naturalness of objects, naturalness of hand and colourfulness) under different SPDs at different CCTs and light levels

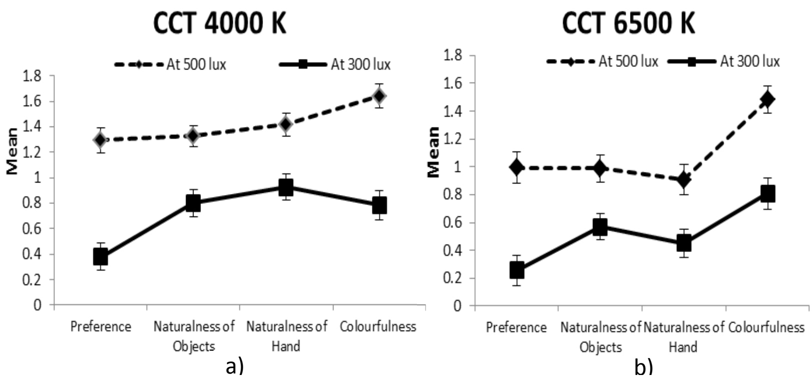

Figure 10. The mean scores for the four scales at 500 lux and at 300 lux for a) 4000 K and b) 6500 K

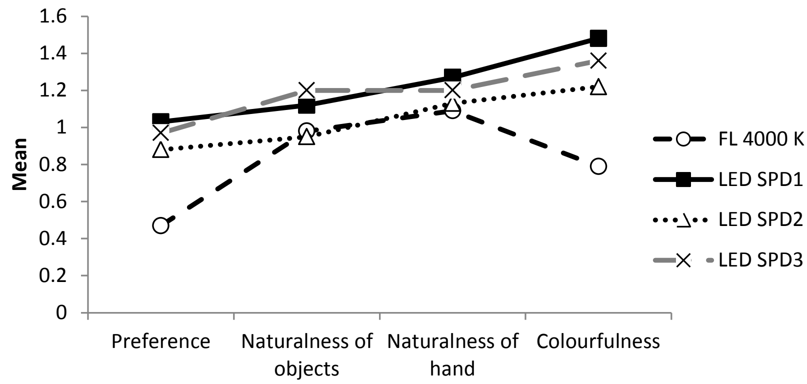

Figure 11. The mean scores for the four scales (preference, naturalness of objects, naturalness of hand and colourfulness) under different SPDs at 4000 K

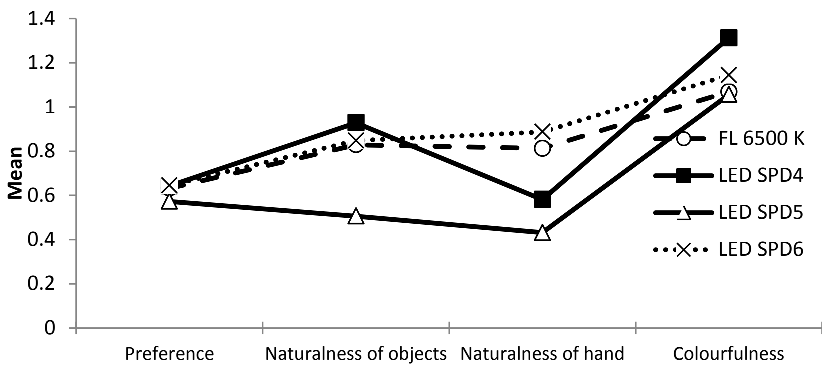

Figure 12. The mean scores for the four scales (preference, naturalness of objects, naturalness of hand and colourfulness) under different SPDs at 6500 K

5.4 Statistical analysis for different SPDs and CCTs

Two-way MANOVA showed that there was no significant interaction between the CCT and SPDs. Therefore, MANOVA was performed for the main factors SPD and the CCTs for the four scales as defined earlier, irrespective of the SPD, age group, ethnicity and gender at light levels of 500 lux and 300 lux.

Statistical analysis for illuminance of 500 lux

The MANOVA showed that the mean scores under CCT of 4000 K were statistically significantly higher than those under CCT of 6500 K for preference, naturalness of objects, and naturalness of hand, whereas no statistically significant differences were found related to the colourfulness (Figure 13).

Statistical analysis for illuminance of 300 lux

No statistically significant differences were found in any scales between 4000 K and 6500 K under any of the SPDs at 300 lux (Figure 13).

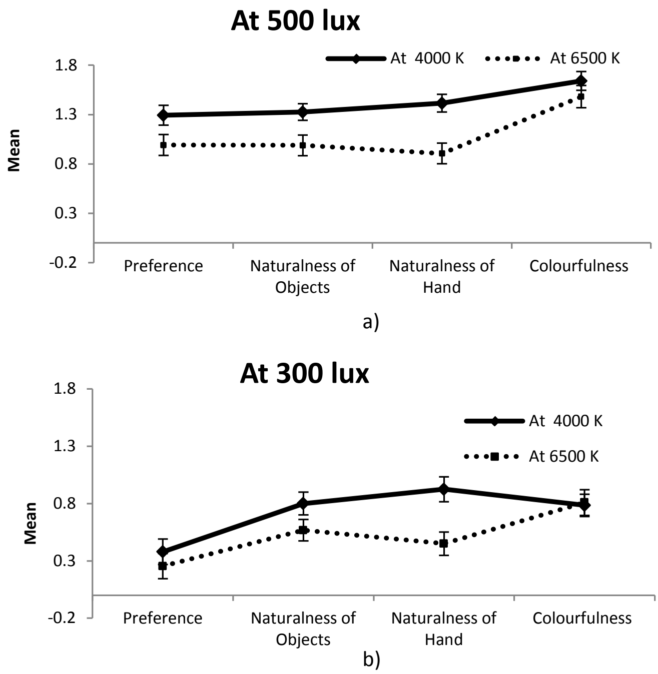

Figure 13. The mean scores for the four scales at 4000 K and at 6500 K for a) 500 lux and b) 300 lux

5.5 Summary

The office room experiments verified the earlier findings regarding LED spectra and conducted in lighting booths (Publications [I, II]). The observers preferred the LED SPDs with higher Qp and Qg or GAI, i.e. LED SPD1, SPD2, SPD3 and SPD4. It was also found that the simpler SPDs (like LED SPD3) can have similar colour quality characteristics to those of the complex LED SPDs with many wavelength peaks (such as LED SPD1). A simple SPD can be generated by using red, mint white (blue LED chip and green-based phosphor) and blue LEDs. Moreover, for the office lighting the observers preferred CCT of 4000 K over CCT of 6500 K at 500 lux. It was also found that the observers preferred the light level of 500 lux over that of 300 lux for office work.

6. Performance of colour fidelity indices

6.1 Introduction

Colour fidelity is one of the important aspects of colour quality. Colour fidelity (also known as colour rendering) of a light source is an effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant[1]. The only internationally recognized metrics for measuring and specifying colour rendering properties of light sources is the CIE colour rendering index (CRI). The studies presented in Chapters 3 -5 showed that the CIE CRI does not describe the naturalness of objects, colourfulness of objects or subjective preferences. This could be expected, as the CIE CRI is a fidelity metric and does thus not necessarily describe other aspects of colour quality. It should define colour fidelity precisely, though. However, CIE CRI provides a poor estimation of the colour-rendering properties of LEDs [5]. CIE CRI has many deficiencies (see Chapter 2). Currently, CIE TC 1-90: colour fidelity index is working to find out the new colour fidelity index. Many new metrics like CQS[20], CRI2012[18] and CRI-CAM02UCS [19] have been proposed. However, no metric has been recommended due to a lack of precise and comprehensive data. Hence, in order to study the performance of different fidelity metrics, the CIE Colour rendering index (CRI), the Colour quality scale (CQS) and the CRI2012, further user acceptance studies in lighting booth were conducted (Publication [VI]).

6.2 Experimental setup

Two viewing booth/cabinets were constructed for the experiment. One cabinet was illuminated by different test LED SPDs and the other cabinet by reference light sources. Experiments were conducted at CCTs of 2800 K, 4000 K and 6500 K. Twenty observers who participated in the experiment had normal visual acuity and colour vision. The average age of the observers was 27 years (standard deviation 4.2 years). The task of the observer was to scale the visual colour difference of chromatic samples of the MCCs and the observer's own hand under reference and test light sources. The observers scaled the visual colour difference with the help of a grey scale (1-5) placed in the reference cabinet.

The LED SPDs were generated with the help of a 12-channel LED-based SPD simulator system, as was done in the previous studies (Publications [I, II]). The LED SPDs were simulated for high, medium and low values of the CIE

CRI. LED SPD1 at 2800 K, 4000 K and 6500 K has high CIE CRI values (Ra>90). LED SPD2 at all CCTs has CIE CRI values of around 80, and LED SPD3 at all three CCTs has low CIE CRI (<60). Halogen lamp (Halolux ceram 64476), Philips Master TL-D 90 De Luxe 18W/940 fluorescent lamp, and Osram 18W/965 Lumilux DE Luxe Daylight fluorescent lamp were used as reference light sources at CCT of 2800 K, 4000 K, and 6500 K, respectively. The colour characteristics of the light sources along with luminance values calculated using the CIE 10° colour matching function are presented in Table 8.

Table 8. Colour characteristics of light sources and luminance used in the study

CCT		Measured CCT	Luminance (cd/m^2)	Duv	CIE CRI	CRI2012	CQS	Qf	Qg	FCI
2800 K	Halogen	2819	144	0.0008	99	100	99	99	97	122
	LED SPD 1	2862	136	-0.0016	94	91	91	90	103	124
	LED SPD 2	2896	141	-0.0049	81	88	88	81	117	146
	LED SPD 3	2871	149	-0.0044	53	67	67	62	130	175
4000 K	FL	3817	143	0.00029	91	87	92	91	100	113
	LED SPD 1	3840	139	-0.00449	91	91	89	86	104	121
	LED SPD 2	3878	145	-0.0033	74	85	83	75	122	148
	LED SPD 3	3861	151	-0.0049	58	77	70	64	128	159
6500 K	FL	6320	142	0.00331	91	87	90	89	101	100
	LED SPD 1	6336	154	-0.00354	92	92	89	88	99	96
	LED SPD 2	6324	147	-0.005	82	93	91	82	116	123
	LED SPD 3	6284	148	-0.00376	60	67	70	65	129	159

6.3 Results

The results obtained from each observer in terms of grade 1-5 were transformed to visual difference (ΔV) in the CIELab colour difference formula. The average visual difference for each sample under different light sources at different CCTs is shown in Figure 14.

The performance of observers' results were examined with the help of observers' repeatability and accuracy, as was done by Li et al [31] (for detail see Publication [VI]). The coefficient of variation (CV) values for the observer repeatability and accuracy are similar among different light sources.

6.3.1 Testing the performance of colour rendering indices

The performances of different indices were tested using the visual colour difference results (ΔV). The visual differences of all test sources plotted on y-axis against the predictions from different indices on x-axis are shown in Figure 15. The visual difference results ranged from 1.9 to 3.7 from the best LED SPD1 to the worst LED SPD3. The LED SPDs (LED SPD1 and LED SPD2) which have high (>80) CIE CRI, CQS and CRI2012 values have low visual colour differences. The LED SPD3 at all three CCTs have higher visual colour differences.

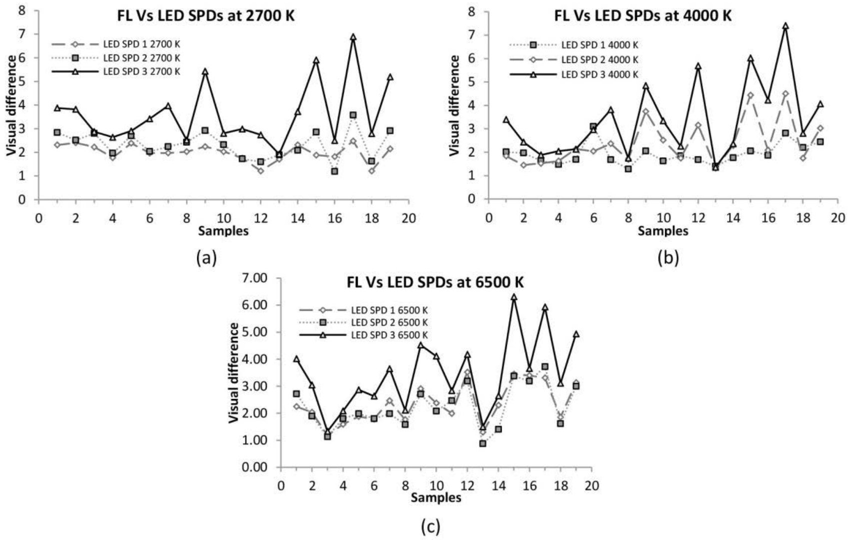

Figure 15. Average visual difference of each colour sample at (a) 2800 K, (b) 4000 K, and (c) 6500 K

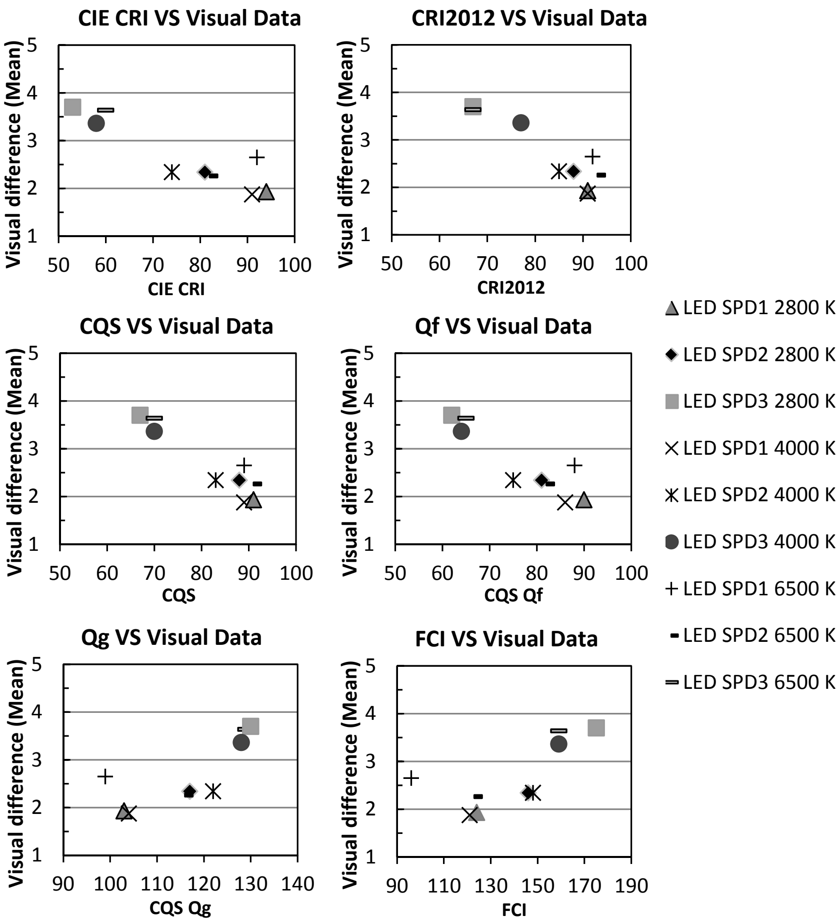

Figure 14. Performance of five indices

The correlation between ΔV and various indices was examined by calculating the Pearson correlation coefficient. The results show that CIE CRI, CRI2012, CQS and CQS Qf are highly correlated with each other and with the visual difference. The results showed that CIE CRI, CQS, Qf and CRI2012 gave similar performance in terms of colour fidelity.

The CRI2012 and CQS values of LED SPD3 at all CCTs (which have Ra≤60), vary from 67 to 77, and visual difference varies from 3 to 3.63. LED SPD3 at 4000 K has CQS, CRI2012, and visual difference values of 70, 77 and 3.4, respectively. On the other hand, for LED SPD3s at 2800 K and 6500 K, the performance of CRI2012 and CQS was similar, and visual differences were 3.08 and 3.63, respectively, LED SPD3s had low CIE CRI, as CIE CRI penalizes the change in chroma [19]. As CQS does not penalize the increase of chroma, CQS values of LED SPD3s were higher than the CIE CRI values. Also, a larger difference in the prediction by CQS and CRI2012 was seen for LED SPD3 at 4000 K, the difference being seven points. The CQS only penalizes the light sources which increase chroma beyond $\Delta C^*ab=10$. The CRI2012 does not have such criterion. This may be the reason why LED SPD3 at 4000 K has a high CRI2012 value and a low CQS value.

6.4 Summary

The experimental results showed that CIE CRI, CRI2012 and CQS provide similar predictions for LED light sources that do not highly increase chroma. The prediction of colour fidelity by the CIE CRI was the worst for a LED light source that enhances object chroma, and the prediction of colour fidelity provided by the CQS metric was better. From this study, it can be seen that the colour fidelity predictions of CQS and CRI2012 were satisfactory, except for the LED SPD3 at 4000 K.

7. Discussion

7.1 Lighting booth experiments

The results from the lighting booth experiments, based both on individual and comparison evaluations, showed that the observers preferred LED SPD2, LED SPD5 at all three CCTs (i.e. 2700 K, 4000 K and 6500 K) for most of the questions related to the naturalness of objects, the colourfulness of MCC chart and the overall preference. The LED SPD2 and LED SPD5 have higher CQS Qp, CQS Qg and GAI values compared to the other SPDs, and the Duv values were either negative or laid very close to the black body locus. The CQS Qp metric is based on the notion that increases in chroma are generally preferred by the observers and should be rewarded. Therefore, LED SPD2 and LED SPD5 should produce the highest perceived chroma of object colours. The CQS Qg and GAI metrics are based upon the gamut area of the reference and test light sources. Generally, the object colours appear more colourful when the gamut area is large[20], [48], [49]. The colourfulness values (calculated using CAM02UCS) of almost all the objects under the LED SPD2 and LED SPD5 were higher than under the other SPDs.

The LED SPD4 and LED SPD6, which have lower CQS Qp, CQS Qg, FCI and GAI values than the other SPDs, were the least preferred light spectra. Under these two SPDs, the chroma and colourfulness values of objects and MCC chart colours were lower than those under all the other SPDs. This showed that when the chroma and colourfulness values of the object colours under a certain illumination increase (up to certain level), the objects appear to be more natural to observers and that lit environment would be preferred by the observers. However, the upper limits for the chroma and colourfulness values that the observers would prefer were not studied.

The LED SPD1, realized for high CIE CRI (around 97), were not preferred by the observers for the naturalness of objects and colourfulness of MCC chart in most cases. The LED SPD1 at all CCTs has high CIE CRI and nCRI values. However, these SPDs were not preferred by the observers. This supports the finding of Nascimento and Masuda [25] who found that the large CIE CRI does not correspond to the most natural colours. The CIE CRI and nCRI are fidelity metrics, and as expected, do not reflect the naturalness of objects, colourfulness of MCC chart and overall preference of the lit environment well.

The LED SPD3 at all CCTs has higher CQS Qp and CQS Qg values than the FL; however, in both evaluations (individual and comparison evaluation) the observers preferred the FL over the LED SPD3. The chroma and the colourfulness values of most of the object colours under the LED SPD3 were also higher than under the FL. However, the Duv values of the FL lay closer to the black body locus than that of the LED SPD3. The LED SPD3 at 6500 K has Duv values greater than 0.0054. The Duv values could be the possible reason why the LED SPD3 was not preferred over the FL despite its higher chroma and colourfulness values. This implies that the CQS Qp, CQS Qg or GAI, and Duv are equally important in defining the naturalness of objects and the overall preference of light sources. These results strongly support the work of Rea and Freyssinier [49] and Guo and Houser [50].

The statistical analysis for the CCT preference data based on the individual evaluations showed that the observers preferred the higher CCTs (4000 K/6500 K) over the lower CCT (2700 K) at the illuminance level of 500 lux. The observers did not prefer the CCT 2700 K for the naturalness of objects and colourfulness of MCC chart. In addition, the observers' mean ratings for visual pleasantness and the visual comfort of the lit scenes at 2700 K were the lowest than at other CCTs.

7.2 Simplified LED SPD

The preferred LED SPDs found in the lighting booth experiments were generated with 9 to 11 different types of LEDs. These LED SPDs will probably not be commercially exploitable due to their complexity. The different LEDs have different temperature behaviour, and the light outputs of the different LEDs change unequally with varying junction/ambient temperature. Hence, simulation of simplified LED spectra was carried out along with the user acceptance studies.

The simulation results presented in Chapter 4 showed that the first trial LED SPD and the fourth trial LED SPD were closely matched with the Aalto SPD, the preferred LED SPD derived from the study presented in Chapter 3 (LED SPD5). The first trial LED SPD uses three types of phosphors and a red monochromatic LED, thus it might be difficult to manufacture and is likely to be expensive. Also, its LER value was low. On the other hand, the fourth trial SPD uses only one type of phosphor and an amber LED. This LED SPD had a comparatively high LER value (327 lm/w). However, the CIE CRI value of the fourth trial LED SPD (Ra=74) was lower than that of the Aalto SPD (Ra=80). The CIE technical committee 1-62 has concluded that '*the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set.*' Therefore, if the CIE CRI is not considered, the fourth trial SPD was the closest matched to the Aalto SPD in terms of CQS Qp and CQS Qg.

The results of the user acceptance studies showed that the naturalness of lemon and the observers' hand, as well as the brightness of light environment inside the booth were higher under the SPD1 than under the reference SPD. However, the colourfulness of objects and MCC chart were better under the reference SPD than under the SPD1. This might be due to the fact that the reference SPD covers a larger gamut area than the SPD1 does. The SPD1 was a simplified LED SPD realized with three different types of LEDs, whereas the reference SPD was the preferred complex LED SPD realised with nine different types of LEDs. In addition, the SPD1 had higher LER value than the reference SPD (256 lm/w) (Table 3). This suggests that the simplified LED SPD, being more cost effective and more efficient, could provide similar or better colour quality characteristics than the preferred complex SPD.

7.3 Office room experiments

The three different LED SPDs and FL at two CCT, i.e. 4000 K and 6500 K, were tested in a real office room. The office room experiments indicated that the observers preferred the light environments under the LED SPDs over the FL at 4000 K for the four scales: preference, naturalness of objects, naturalness of hand and colourfulness. The LED SPDs at 4000 K have high CQS Qp, CQS Qg, GAI and FCI values compared to the FL at 4000 K (Figure 16). Both the LED SPD1 and the LED SPD2, have high CQS Qp and CQS Qg values. The Duv value of the LED SPD1 was negative, whereas the Duv value of the LED SPD2 was positive. Yet the observers preferred both the LED SPDs over the FL. However, the observers' mean ratings for the LED SPD1 were higher than those for the LED SPD2. This shows that if the light sources have the same CQS Qp and Qg values, then observers prefer the light source with a negative Duv value (i.e. 0 to - 0.0054).

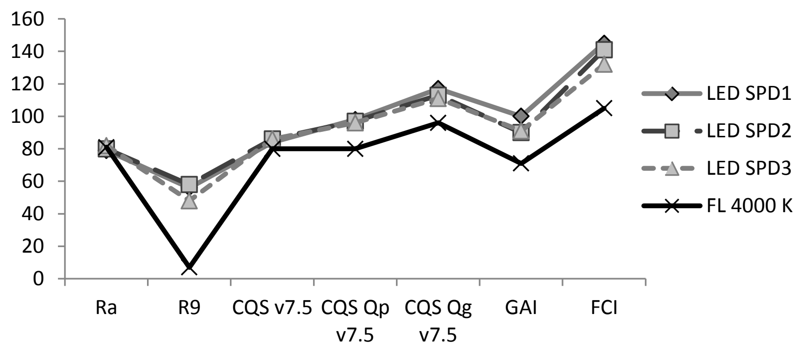

Figure 16. Comparison of different metrics; Ra, R9, CQS, CQS Qp, CQS Qg, GAi and FCI for different light sources at 400 K used in the experiment

The LED SPD1 was realised with the help of 11 different types of LEDs, whereas the LED SPD3 was realised using three different types of LEDs: Red, Mint white (Blue LED Chip and green-based phosphor) and Blue LEDs. The peak wavelengths of the Red, Mint white and blue LEDs were 658 nm, 639 nm and 448 nm, respectively. The CIE CRI, CQS Qp and CQS Qg values of the LED SPD3 were close to those of the LED SPD1 and the LED SPD2. The observers preferred the LED SPD3 to FL for the preference and colourfulness scales. The mean scores for four scales (naturalness of objects, naturalness of hand, colourfulness and preference) for the LED SPD1 (around 1.03 to 1.48) and LED SPD3 (around 0.97 to 1.36) were close to one another in most cases. This suggests that the simplest LED SPD with three peaks may have colour quality characteristics similar to the complex LED SPD (with many peaks, as in the LED SPD1). The observers will still prefer the simplest LED SPD over FL, given that the CQS Qp, CQS Qg or GAI values for that LED SPD are high. The findings support the work of Viénot *et al* [51]. They concluded that LED clusters which include white LEDs and a few correcting coloured LEDs can render colours faithfully.

At 6500 K, no significant differences in the four scales were found between the light source spectra. However, the observers' mean ratings for the lighting environment under the LED SPD4 and the LED SPD6 were higher than under the other SPDs. This was found for preference, naturalness of objects and colourfulness scales (Figure 12). These two SPDs have high CQS Qp and CQS Qg values, and both of these SPDs cover a larger gamut area compared to the FL and the LED SPD5.

The statistical analysis showed that the observers preferred the CCT of 4000 K over 6500 K at 500 lux in terms of preference, naturalness of objects and naturalness of hand. Moreover, the same CCT was preferred at 500 lux in terms of comfort, pleasantness of light colour and acceptance of the lit environment in the entire room (Publication [V]). This supports the findings of Shamsul *et al* [37], Kang *et al* [38] and Cockram *et al* [41]. However, Boyce and Cuttle [44] found that '*the CCT of good colour rendering lamps in the range of 2700 K to 6300 K has little effect on people's impressions of the lighting of the room.*' Also, Lin *et al* [29] found that CCTs of 4000 K and 7000 K at 600 lux were preferred for office lighting. The preferences of CCTs depend upon personal experiences and the traditional culture, are totally subjective matters. However, this study showed that neutral white light (4000 K) is preferable to cool white light (6500 K) for office lighting with LEDs.

The study also showed that the observers preferred the illuminance of 500 lux over 300 lux at 4000 K and 6500 K. The observers rated all the questions under different SPDs at 500 lux comparatively higher than at 300 lux. Furthermore, the scores at 300 lux for preference, naturalness of hand, naturalness of objects and colourfulness scales under different SPDs were close to each other (Figure 13). It seems that, at lower illuminance, the observers felt more difficult to evaluate the differences in the light environment. This finding does not fall in line with the Kruithof's curve [43]. The observers did not feel comfortable and did not prefer the light level of 300 lux at both CCTs. They felt that at illuminance of 500 lux the objects appeared more natural and more colourful than at 300 lux. Also, the observers preferred the illuminance of 500 lux to 300 lux at both CCTs for the questions related to spatial brightness and overall spaciousness (Publication [V]). This supports the findings of Boyce and Cuttle [44] who found that as '*the light level increases, the lighting of the room becomes more natural, more colourful, more pleasant, more comfortable, clearer, bright, more friendly more warm and more uniform.*'

7.4 Colour fidelity

The colour fidelity experiments showed that the LED SPDs having high CIE CRI (>90), also possess higher CRI2012, CQS and CQS Qf values. Also, the test samples had lower visual differences under these SPDs. However, the LED SPD3 at all CCTs has low CIE CRI values (i.e. ≤60), CRI2012 and CQS values vary from 67 to 77 and visual difference under the LED SPD3 varies from 3.3 to 3.7. The LED SPD3 at 4000 K has CQS, CRI2012, and visual difference values of 70, 77 and 3.4, respectively. On the other hand, for the LED SPDs 3 at 2800 K and 6500 K, the performance of CRI2012 and CQS were similar, and visual differences were, 3.6 and 3.7, respectively. Most of the test samples under the LED SPD3 have a larger chroma than under the reference light sources (see Publication [VI], Figure 7). Since, CIE CRI penalizes changes in chroma [20], the LED SPD3 had low CIE CRI values. In contrast, the CQS does not penalize the increases of chroma, hence CQS values of LED SPD3s were higher than the CIE CRI values. Also, a larger difference in the prediction by CQS and CRI2012 was seen for the LED SPD3 at 4000 K, the difference being seven points. The CQS only penalizes light sources which increase chroma beyond $\Delta C^*_{ab}=10$. The CRI2012 does not have such criterion. This may be the reason why LED SPD3 at 4000 K has a high CRI2012 value and a low CQS value. In addition, the performances of CIE CRI, CRI2012, CQS and CQS Qf in terms of correlation coefficient (with visual difference) were very similar.

8. Conclusions

The lighting booth experiments indicated that the observers preferred the LED SPDs (LED SPD2 and LED SPD3) that have high CQS Qp and CQS Qg or GAI values at all three CCTs (Publications [I, II]). The observers felt that the objects looked more natural and more colourful under the LED SPD2 and under the LED SPD3. The observers also found that the light environments under these SPDs were visually brighter, more comfortable and more pleasant. Along with metrics like CQS Qp and CQS Qg or GAI, the study showed that the Duv values of light sources also affect the subjective preferences. The observers preferred light sources whose Duv values were in between 0 and -0.0054, along with high CQS Qp and CQS Qg. The study also showed that at illuminance level of 500 lux the observers preferred light sources with CCTs of 4000 K and 6500K over 2700 K.

The work was continued by simulation carried out to find out the simplified LED SPDs that the observer will prefer, as the preferred LED SPDs found in the lighting booth experiments were of a complex nature and obviously expensive to realize. The simulation results suggested that it is possible to generate simplified LED SPDs which have CQS Qp and CQS Qg values similar to those of the preferred complex SPDs. The user acceptance studies also indicated, that the simplified LED SPDs can provide similar or better colour quality characteristics than the complex LED SPDs. The simplified LED SPDs used in the user acceptance studies were generated using three different types of LEDs; Red, cool white and Blue LEDs. Similar results were found when the simplified LED SPDs with CCT of 4000 K were tested in an office room. The observers preferred the simplified LED SPD over the FL.

The office room experiments verified the findings of the light booth experiments. The observers preferred the most the LED SPDs with high CQS Qp and CQS Qg or GAI values, and preferred the least the LED SPDs that had the lowest CQS Qp and CQS Qg values. Also, the light sources (which have high CQS Qp and CQS Qg) with negative Duv values were preferred over light sources with positive Duv values. It was found that the values should be within the limits of ±0.0054. Moreover, for office lighting, the observers preferred the CCT of 4000 K over the CCT of 6500 K at 500 lux. It was also found that the observers' ratings of preference were influenced by the illuminance level. The observers preferred the illuminance level of 500 lux to that of 300 lux for office work.

The results of performance testing of different fidelity metrics conducted in the lighting booths showed that the CIE CRI, CRI2012 and CQS provide similar predictions for LED light sources which do not highly increase the object chroma. The predictions of colour fidelity for LED light sources that enhances object chroma were the best by the CQS and the worst by CIE CRI. This study indicates that the colour fidelity predictions of the CRI2012 and the CQS were satisfactory (except for the LED SPD3 at 4000 K).

In general, this study indicates that the subjective preferences (in terms of naturalness, colourfulness, comfort, pleasantness, brightness and the overall preference) can be explained better when a reference-based metric (such as CQS Qp) and an area-based metric (such as Qg or GAI) are both considered, and when the light source chromaticity difference (Duv) value is maintained within the limits of ±0.0054. Also, the findings indicate that people prefer LED light sources at 4000 K at illuminance level of 500 lux for office work. Moreover, the predictions of colour fidelity provided by the CQS for LED light sources that enhance object chroma were the best. However, further studies are needed considering other metrics such as the rank-order colour rendering index (RCRI) [52], the categorical colour rendering index (CCRI) [53] and the Harmony rendering index (HRI) [54], as these metrics consider other aspects of colour quality. Moreover, more experimental data using LED light sources that highly increase object chroma and with materials that correspond to everyday materials for which people care about colour fidelity are required before choosing any final colour fidelity metric(s).

References

[1] Commission Internationale de l'Éclairage, "Standard ILV : International Lighting Vocabulary," 2011.

[2] J. Schanda, "CIE Colorimetry," in *Colorimetry: Understanding the CIE System*, John Wiley & Sons, Inc., 2007, pp. 25–78.

[3] Commission Internationale de l'Éclairage, "Method of Measuring and Specifying Colour Rendering Properties of Light Sources," Vienna, Austria, CIE Technical Report, CIE 13.3: 1995, 1995.

[4] J. Schanda, "Colour rendering of light sources," in *Colorimetry: Understanding the CIE System*, New YorkJohn Wiley and Sons, Inc., 2007, pp. 207–215.

[5] Commission Internationale de l'Éclairage, "Colour rendering of white LED light sources," Vienna, Austria, CIE Technical Report, CIE 177: 2007, 2007.

[6] X. Guo and K. W. W. Houser, "A review of colour rendering indices and their application to commercial light sources," *Light. Res. Technol.*, vol. 36, no. 3, pp. 183–199, Sep. 2004.

[7] IESNA (Illuminating Engineering Society of North America), *The IESNA Lighting Handbook-Reference and application*, 9th ed. New York, USAIESNA, 2000.

[8] Commission Internationale de l'Éclairage, "A Review of Chromatic Adaptation Transforms," Vienna, Austria, CIE Technical Report, CIE 160: 2004, 2004.

[9] N. Narendran, N. Maliyagoda, L. Deng, and R. Pysar, "Characterizing LEDs for general illumination applications: mixed-color and phosphor-based white sources," in *Proceedings of SPIE 4445: Solid State Lighting and Displays*, 2001, San Diego, CA, USASPIE, pp. 137–147.

[10] Y. Ohno, "Spectral design considerations for white LED color rendering," *Opt. Eng.*, vol. 44, no. 11, p. 111302, Nov. 2005.

[11] N. Sándor, P. Bodrogi, P. Csuti, B. Kranicz, and J. Schanda, "Direct visual assessment of colour rendering," in *Proceedings of*

the 25th Session of the CIE, 2003, San Diego, USA, pp. D1–42–45.

[12] T. Tarczali, P. Bodrogi, and J. Schanda, “Colour rendering properties of LED sources,” in *Proceedings of the 2nd CIE Expert Symposium on LED Measurement: Standard Methods for Specifying and Measuring LED and LED Cluster Characteristics*, 2001, Gaithersburg, USA.

[13] J. Schanda, “The concept of colour rendering revisited,” in *Conference on Colour in Graphics, Imaging, and Vision*, 2002, Society for Imaging Science and Technology, pp. 37– 41.

[14] N. Sándor, P. Csuti, P. Bodrogi, and J. Schanda, “Visual observation of colour rendering,” in *Proceedings of the CIE Expert Symposium on LED Light Sources: Physical Measurement and Visual and Photobiological Assessment*, 2004, Tokyo, Japan, pp. 16–19.

[15] N. Sándor and J. Schanda, “Visual colour rendering based on colour difference evaluations,” *Light. Res. Technol.*, vol. 38, no. 3, pp. 225–239, Sep. 2006.

[16] N. Narendran and L. Deng, “Color Rendering Properties of LED Light Sources,” in *International Symposium on Optical Science and Technology*, 2002, International Society for Optics and Photonics, pp. 61–67.

[17] P. Bodrogi, S. Brückner, and T. Q. Khanh, “Dimensions of light source colour quality,” in *Conference on Colour in Graphics, Imaging, and Vision*, 2010, Society for Imaging Science and Technology, pp. 155–159.

[18] K. a. G. Smet, J. Schanda, L. Whitehead, and R. M. Luo, “CRI2012: A proposal for updating the CIE colour rendering index,” *Light. Res. Technol.*, vol. 45, no. 6, pp. 689–709, Jun. 2013.

[19] C. Li, M. Ronnier Luo, C. Li, and G. Cui, “The CRI-CAM02UCS colour rendering index,” *Color Res. Appl.*, vol. 37, no. 3, pp. 160–167, Jun. 2012.

[20] W. Davis and Y. Ohno, “Color quality scale,” *Opt. Eng.*, vol. 49, no. 3, pp. 033602:1–16, Mar. 2010.

[21] M. S. Rea and J. P. Freyssinier-Nova, “Color rendering: A tale of two metrics,” *Color Res. Appl.*, vol. 33, no. 3, pp. 192–202, Jun. 2008.

[22] S. Jost-Boissard, M. Fontoynont, and J. Blanc-Gonnet, “Perceived lighting quality of LED sources for the presentation of

fruit and vegetables," *J. Mod. Opt.*, vol. 56, no. 13, pp. 1420–1432, Jul. 2009.

[23] K. A. G. Smet, W. R. Ryckaert, M. R. Pointer, G. Deconinck, and P. Hanselaer, "Memory colours and colour quality evaluation of conventional and solid-state lamps," *Opt. Express*, vol. 18, no. 25, pp. 26229–26244, 2010.

[24] K. Smet, W. R. Ryckaert, M. R. Pointer, G. Deconinck, and P. Hanselaer, "Correlation between color quality metric predictions and visual appreciation of light sources.," *Opt. Express*, vol. 19, no. 9, pp. 8151–8166, Apr. 2011.

[25] S. M. C. Nascimento and O. Masuda, "Psychophysical optimization of lighting spectra for naturalness, preference, and chromatic diversity.," *J. Opt. Soc. Am. A. Opt. Image Sci. Vis.*, vol. 29, no. 2, pp. A144–52, Feb. 2012.

[26] K. Smet, W. Ryckaert, M. Pointer, G. Deconinck, and P. Hanselaer, "Optimization of colour quality of LED lighting with reference to memory colours," *Light. Res. Technol.*, vol. 44, no. 1, pp. 7–15, Jan. 2012.

[27] W. Ryckaert, K. Smet, I. Roelandts, M. Van Gils, and P. Hanselaer, "Linear LED tubes versus fluorescent lamps: An evaluation," *Energy Build.*, vol. 49, no. 2012, pp. 429–436., 2012.

[28] N. Pousset, G. Obein, and A. Razet, "Visual experiment on LED lighting quality with color quality scale colored samples," in *Proceedings of CIE 2010: Lighting Quality and Energy Efficiency*, 2010, no. March, Vienna, Austria, pp. 722–729.

[29] R. F. Lin, C. Chou, Y. Wang, and H. Tu, "Effects of LED Color Temperature on Office Workers," in *In The 2nd Southeast Asian Network of Ergonomics Societies Conference*, 2012, Langkawi, Malaysia.

[30] J. Spaulding, R. Maria, and E. Robert, "Human preference in tunable solid state lighting," in *Proceeding SPIE 7954, Light-Emitting Diodes: Materials, Devices, and Applications for Solid State Lighting XV, International Society for Optics and Photonics*, 2011, , pp. 795403–1–795403–11.

[31] C. Li, M. Ronnier Luo, G. Cui, and C. Li, "Evaluation of the CIE colour rendering index," *Color. Technol.*, vol. 127, no. 2, pp. 1–7, 2011.

[32] M. R. Luo, Y. H. Chao, H. S. Chen, P. L. Sun, J. Liao, and A. Lin, "Testing Colour Rendering Indices," in *Lighting quality and Energy Efficiency*, 2012, Hangzhou, ChinaCIE, pp. 168–172.

[33] Commission Internationale de l'Éclairage, "A colour appearance model for colour management systems: CIECAM02," Vienna, Austria, CIE Technical Report, CIE 159: 2004, 2004.

[34] I. Schröder, "Subjective responses to light sources of different colour temperatures and illuminances.," *Z. Morphol. Anthropol.*, vol. 81, no. 2, pp. 235–251, 1996.

[35] M. Wei, K. Houser, B. Orland, D. Lang, N. Ram, M. Sliwinski, and M. Bose, "Office worker response to fluorescent lamps of different CCT and lumen output," in *Proceedings of 2013 Architectural Engineering Institute*, 2013, Pennsylvania, USAASCE (American Society of Civil Engineers) 2013, pp. 554–563.

[36] X. Hu, K. Houser, and D. Tiller, "Higher color temperature lamps may not appear brighter," *Leukos*, vol. 3, no. 1, pp. 69–81, 2006.

[37] B. Shamsul, C. Sia, Y. Ng, and K. Karmegan, "Effects of light's colour temperatures on visual comfort level, task performances, and alertness among students," *Am. J. Public Heal. Res.*, vol. 1, no. 7, pp. 159–165., 2013.

[38] M. Kang, J. Chang, Y. Yoon, and S. Kim, "Determining occupant-friendly lighting environments for the improvement of visual perception," in *ICSDEC 2012: Developing the Frontier of Sustainable Design, Engineering, and Construction*, 2012, Texas, USAASCE (2013), pp. 937–944.

[39] B. Park, J. Chang, Y. Kim, J. Jeong, and A. Choi, "A study on the subjective response for corrected colour temperature conditions in a specific space," *Indoor Built Environ.*, vol. 19, no. 6, pp. 623–637, 2010.

[40] B. Manav, "An experimental study on the appraisal of the visual environment at offices in relation to colour temperature and illuminance," *Build. Environ.*, vol. 42, no. 2, pp. 979–983, 2007.

[41] A. Cockram, J. Collins, and F. Langdon, "A study of user preferences for fluorescent lamp colours for daytime and night-time lighting," *Light. Res. Technol.*, vol. 2, no. 4, pp. 249–256, 1970.

[42] O. Masuda and S. M. C. Nascimento, "Best lighting for naturalness and preference," *J. Vis.*, vol. 13, no. 7, Jun. 2013.

[43] A. A. Kruithof, "Tubular luminescence lamps for general illumination," *Philips Tech. Rev.*, vol. 6, no. 3, pp. 65–96, 1941.

[44] P. Boyce and C. Cuttle, "Effect of correlated colour temperature on the perception of interiors and colour discrimination performance," *Light. Res. Technol.*, vol. 22, no. 1, pp. 19–36, 1990.

[45] F. Viénot, M. Durand, and E. Mahler, “Kruithof’s rule revisited using LED illumination,” *J. Mod. Opt.*, vol. 56, no. 13, pp. 1433–1446, 2009.

[46] R.-H. Huang, L. Lee, Y.-A. Chiu, and Y. Sun, “Effects of correlated color temperature on focused and sustained attention under white LED desk lighting,” *Color Res. Appl.*, Apr. 2014.

[47] S. Fotios, “Chromatic adaptation and the relationship between lamp spectrum and brightness,” *Light. Res. Technol.*, vol. 38, no. 1, pp. 3–17, Jan. 2006.

[48] J. Freyssinier and M. Rea, “A two-metric proposal to specify the color-rendering properties of light sources for retail lighting,” in *Proceeding of SPIE 2010: Tenth International Conference on Solid State Lighting*, 2010, , p. 77840V–77840V–6.

[49] M. S. Rea and J. P. Freyssinier, “Color rendering: Beyond pride and prejudice,” *Color Res. Appl.*, vol. 35, no. 6, pp. 401–409, Dec. 2010.

[50] K. W. Houser, M. Wei, A. David, M. R. Krames, and X. S. Shen, “Review of measures for light-source color rendition and considerations for a two-measure system for characterizing color rendition,” *Opt. Express*, vol. 21, no. 8, pp. 10393–10411, 2013.

[51] F. Viénot, E. Mahler, J. J.-J. Ezrati, C. Boust, A. Rambaud, and A. Bricoune, “Color Appearance under LED Illumination: The Visual Judgment of Observers,” *J. Light Vis. Environ.*, vol. 32, no. 2, pp. 208–213, 2008.

[52] T. Khanh, P. Bodrogi, and S. Brückner, “Rank-order based description of colour rendering: definition, observer variability and validation,” pp. 143–147, 2010.

[53] H. Yaguchi, H. Takahashi, and S. Shioiri, “A proposal of color rendering index based on categorical color names,” in *International Lighting Congress*, 2001, Istanbul.

[54] F. Szabo, P. Bodrogi, and J. Schanda, “A colour harmony rendering index based on predictions of colour harmony impression,” *Light. Res. Technol.*, vol. 41, no. 2, pp. 165–182, May 2009.

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Light emitting diode (LED) based lighting technology is developing rapidly. LED lighting has huge potential to save energy and provides enormous opportunities to adjust the lighting according to actual needs. However, end-users' requirements, expectations and preferences for lighting applications based on LEDs are not well known. Therefore, visual evaluations are required to find out the subjective preferences for different LED SPDs. In addition, metric(s) that better defines the subjective preferences and colour rendering properties of light sources are need. This thesis investigates the subjective preferences for lighting environments under different LED SPDs in several viewing conditions and correlates the preferences and corresponding SPDs with existing metrics of colour quality.

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